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REVIEW ARTICLE

Holonic thinking and systemic creativity in sport education: A new paradigm for collective tactical training

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ABSTRACT

The holonic approach in sports education offers a new paradigm for collective tactical training, moving beyond rigid and hierarchical models. This study explores how systemic creativity enhances team performance by integrating individual autonomy with collective adaptability. Players function as holons, self-organizing units that dynamically interact within a structured system, fostering emergent tactical patterns. The research highlights how team coordination and decision-making improve when tactical structures are designed to be flexible and responsive rather than rigid. By shifting from fixed positional roles to adaptive interactions, players develop a deeper situational awareness, enhancing strategic cohesion. This study emphasizes the practical applications of holonic thinking in sports, demonstrating how it can optimize team dynamics, creativity, and performance. The findings suggest that holonic structures in training and gameplay lead to greater tactical intelligence, reinforcing the importance of self-organization and adaptive strategies in modern sports education.

Keywords: Physical education, Holonic theory, Systemic creativity, Tactical training, Self-organization, Adaptability, Team dynamics, Sports education, Decision-making.

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INTRODUCTION

The intellectual legacy of Arthur Koestler (1905-1983) trespasses his times and still offer today a modern perspective for studying, interpreting and manage complex systems, the sport education included.

Koestler was one of the most widely read and appreciated journalist, writer and essayist of his time, and an original scholar of the "*human condition*" (Watson, 1999). In 1967 he wrote "*The Ghost in the Machine*", where he first used the term "*holon*", a concept that was further developed in 1970 in his article "*Beyond Atomism and Holism-the concept of the holon*".

The conceptualization of the term "*holon*" found its grounds in the attempt to overcome the dichotomy between holism and reductionism and to take into account both the individualistic and integrative tendencies of whatever agent interacting within whatever complex system. This concept implies the non-existence in nature of autonomous units indivisible and separate as well as the oxymoron nature of the term "*individual*".

Koestler (1970) notes that "*whenever there is life, it must be hierarchically organized*", but the term "*hierarchy*", as Koestler notes, is a non-appropriate as it is full of military reminiscences and generates the idea of a rigidly authoritarian structure. Koestler's hierarchy has quite another meaning: it is a structure with many levels, branched and stratified. A system that branches into subsystems, a structure that encapsulates substructures, of a process that activates sub-processes. For this reason holons start from the hierarchy and move over the hierarchy. Their organization is in the same time hierarchical (pyramidal) and heterarchic (horizontal), for which Koestler coined the term Olarchy (hierarchy + heterarchy).

From the analysis of biological systems to that of human systems, the step is short. The "*holonic*" theory is also a candidate for the study of models of human social systems, because it is able to analyse both the micro-level of individuality and the macro-level of the community.

The next and inevitable step is the recognition that organisms and societies have the same holarchical structure. Koestler attempted to re-establish a sociological thought, encompassing the current epistemological fracture that separate, in a sort of new Cartesian view of society, structure and agent as different poles of the sociological reasoning. Such a fracture, generating "*dichotomies*", still has some appeal in sociology as it should allow to mediate between "*two strong and opposite positions*" as, according to Jenks (1988) "…*we reason in the form of dichotomies here because they enable us to establish arguments from two strong and opposite positions and because they will you also to engage with debates from both sides and to see the strengths of the arguments on both sides*." Koestler, instead, imagined a study of human social structure based on an original approach in which the single concepts of "*holon*", as well as the equivalent structure and agent, could be merged and then be overcome. Koestler's ambition was to find a new epistemology in which to leave behind forever the fruitless dichotomies.

The concept of "*holon*" designates an entity that is, at the same time, something defined in itself and a part of a larger whole. An atom is defined in itself, but it is also part of something more complex when it participates in the structure of a molecule. When the molecule participates in the cellular structure it is a holon, inserted in a more complex system. An organ is a part in itself and, at the same time, a part of an organism.

Up to this point, everything seems to be a consolidated discourse, and therefore not original, about the emergent properties of the higher levels of organization that cannot be predicted starting from levels of lower complexity (von Bertalanffy, 1952). Instead, it is about the identification of a hierarchical model that considers the hierarchy of relationships in an innovative way. In this regard, as explicitly quoted by Koestler (1970), this concept was derived from the general system theory of Ludwig von Bertalanffy and from what the same von Bertalanffy underlined in his book "*Problems of life; an evaluation of modern biological thought*"(1968): "*Hierarchical organization on the one hand, and the characteristics of open systems on the other, are fundamental principles of living nature"* [quoted by Koestler (1970)].

Reality can be seen as an infinite series of holonic relationships. Holons have action, individuality, autonomy, commonality, mutuality and collective relationships. They have the ability to transform into larger full-scale agents and to emerge creatively and indefinitely. Koestler (1970) notes that parts and wholes have no absolute value in nature, what matters is the way in which parts and wholes are holarchically related. Koestler uses the concept of "*holon*" for an interpretation of nature that ranges from the examination of the structure of the brain to the "*holonic*" interpretation of ontogenesis.

The holonic theory was widely used, in recent years, in a broad range of sectors, spanning from manufacturing systems (Babiceanu and Chen, 2006; Valckenaers et al., 1998) to urban planning (Boudjemaa and Ridda Laouar, 2006), from multi-agent systems (Beheshti et al., 2016) to climate change communication (Briggs, 2007) and industrial ecology (Kay, 2003).

The holonic theory does not seems to appeal sport education, even though it appears to have a great potentiality in this field, as demonstrated, for instance, by the interest this theory raised in the educational field at large. Recently, Galifa (2019), reasoning about the popularity of the teaching process based on "*thinking skills*" (Wegerif, 2002) - much appreciated in our informatics era -, expressed the idea that a shift of paradigm towards a more complex systems of thought is needed. Thinking skill, by the way, seems an elusive concept. Wegerif (2202) define it as "*a desire to teach processes of thinking and learning that can be applied in a wide range of real-life contexts […] information-processing, reasoning, enquiry, creative thinking and evaluation*". Ennis (1985) in his seminal article "*A logical basis for measuring critical thinking skills", defined thinking skills as […] reflective and reasonable thinking that is focused on deciding what to believe or do*", whereas Paul and Elder (2006) definition is "*the art of analysing and evaluating thinking with a view to improve it*". We believe is hard to construct an epistemology on so elusory arguments. Galifa (2018; 2019), instead, preconizes a sort of merging the General System Theory (von Bertalanffy's, 1968; Boulding, 1956) with the Koestler's holonic theory. We will afford this topic in the next section of this work, whereas the potential use of the holonic approach in sport education will be the section concluding our essay.

The rational of this approach is that the application of Koestler's holonic theory (1970) to the world of sports and sports education offers an innovative perspective for understanding team dynamics and tactical training. While traditional approaches to tactical preparation have focused on rigid and hierarchical models, the concept of systemic creativity opens up new possibilities for developing more adaptable and fluid collective strategies. This paradigm perfectly aligns with Koestler's holarchy theory (1967), in which each player is viewed as a holon—an autonomous yet interdependent unit, capable of dynamically interacting within the team, considered as a system. In team sports, creativity is often perceived as a chaotic element that may interfere with a team's strategic organization. However, Memmert (2015) demonstrated that tactical creativity is not synonymous with anarchy, but rather a refined balance between individual improvisation and collective coherence. McGarry et al. (2002) argue that the most effective teams are not those that rigidly follow a set pattern, but rather those that can generate emergent responses based on the interactions between players. This principle is consistent with the concept of holarchy, in which the game is viewed as a continuously evolving ecosystem rather than a linear sequence of predefined actions. Self-organization, defined by Kelso (1995) as the ability of a system to structure itself without a centralized command, is a key concept in systemic creativity applied to sports. The coach cannot predict every possible tactical scenario but can create an environment that fosters real-time creative and effective decision-making. Passos et al. (2008) highlighted how training based on situational creativity leads to an improvement in decision-making ability and the effectiveness of team strategies. This approach finds practical application in models such as the Tactical Games Approach (Hastie et al., 2025), which emphasizes tactical understanding and strategic thinking over mere technical execution. A practical example of the application of systemic creativity is Tiki-Taka, the football philosophy developed by Guardiola's Barcelona (Lago-Peñas et al., 2010). In this system, each player acts as a holon, making independent decisions while remaining aligned with the collective team dynamics. Tactical flexibility is maximized through:

- Function redundancy (multiple players capable of performing the same role).
- Interconnection strength (instant understanding between teammates).

This holonic and adaptive approach allows teams to be more fluid, responsive, and strategically intelligent, creating emergent tactical patterns that enhance collective performance.

THE SPORT EDUCATION TODAY

Sport education, in accordance with the theoretical aspects pertaining to all educational fields, deals with the subjective and personal nature of both teaching and learning experience (Sequeira, 2017). Motor education is aimed at individuals experiencing a peculiar education conveyed both through mind and body. In this context, the body assumes an extremely relevant importance as the bodily perception of the learning subject interacts unceasingly with an ever changing surrounding environment. This continuous transformation is able to generates new knowledge and skills making the sport teaching a particularly challenging experience for both teacher and pupil (Ceciliani, 2018).

Today, constructivist and situated learning perspectives are considered as leading conceptualizations to the teaching and learning in physical education (Dyson et al., 2004). In this frame of reference, three student-cantered models to learning (namely Sport Education, Tactical Games, and Cooperative Learning) seem to have the potential to embody situated learning within a social constructivist theoretical coordinate system.

According to Dyson et al. (2004) Sport Education is "*a functional model which links the sport taught in physical education to the wider sporting culture. system of tasks and learning activities are planned that will result in students not only becoming more skilled, but understanding the histories, traditions, and nuances of the sport, as well as becoming willing participants within the wider sport culture*." This line of thought is very much consistent to the Structural Functionalism defined as "*a framework for building theory that sees society as a complex system whose parts work together to promote solidarity and stability*" (Macioni and Gerber, 2011). The filiation from the general system theory is glaringly evident.

The Sport Education approach is a pedagogical endeavour aimed at involving students not only in learning the fundamental practical and theoretical basis of a specific sport discipline, but also to learn how to leader a team, in the broadest meaning of the term, and take responsibilities for the management of a team. The roles students are called to take on different roles other than those of player (coach, referee, captains, etc.).

Lave and Wenger's, in their seminal book of 1991, introduced the concept of "*situated learning*" by placing the didactical emphasis on the whole person, viewed as constitutive agent operating and interacting within a complex system. These authors overcome, that way, the approach to learning procedures seen as somewhat passive transmission of factual concepts and information, unravelling, in the meantime, the profound social character of education. The Sport Education approach fully falls back into this line of thought as it interprets the learning process as a way to participate in communities of practice.

Dyson et al. (2004) put the emphasis on a second sport learning strategy, other than Sport Education: the Tactical Games. This is a didactical method aimed at reducing the hindrance of the technical aspects of the game, appropriately tuning some rules of the game, thus allowing participants to understand and develop, step by step, both technical and tactical characteristics of the game.

The Tactical Game approach allows student to discover the underpinning similarities pertaining to different games in a sort of "*holistic*" view of games. Having specific array of games similar tactical problems, the understanding of them assists in transferring performance from one game to another as they are framed in a similar technical and tactical structure.

A third learning model envisaged by Dyson et al. (2004) is the Cooperative Learning. The theoretical basis of such an instructional model were defined by Johnson and Johnson (1999) in a seminal article that exerted wide influence on pedagogy. It can be defined as instructional strategy enabling small groups of students to work together on a common assignment. Each student becomes a meaningful participant in learning and can be individually responsible for their part or role in the assignment. Cooperative Learning (CL) also has social outcomes such as positive inter-group relations, the ability to work collaboratively with others. This teaching method is also able to develop social skills, as the group members gain awareness of the importance of interpersonal, social, and collaborative skills. It is easy to see in filigree both the foundations of holonic theory and those of general systems theory.

FROM GENERAL SYSTEM THEORY TO INTEGRAL THINKING AND INTEGRAL EDUCATION

Richardson (2004), in this preface to the reprint of Boulding's "*General systems theory: The skeleton of science*" quoted the following Boulding's sentence "… *such a theory would be almost without content, for we always pay for generality by sacrificing content, and all we can say about practically everything is almost nothing*." The Boulding's caveat refers to one of the most common criticisms moved to the General System Theory, sometime perceived as a "*theory of everything*".

Contrary to such a criticism, the basic and more typical feature of the theory is the attempt to identify universal principles applying to system in general, irrespective of the nature of the system itself (von Bertalanffy, 1968). Such a need was recognised as imperative by von Bertalaffy (1969) because the expanding fragmentation in disciplines, as well as and the ever increasing progress in scientific and technological research, are sharpening the antithesis between mechanism and vitalism. Such an antithesis is perceived by von Bertalanffy (1952) as the most important antipodal confrontation of biological thought in need to be reconciled through an "*organismic conception*", that take shape in a mathematical formulated general theory of systems (Gregg, 1953).

Considering the works of Boulding (1956) and von Bertalanffy (1969), as well as the excellent review of Laszlo and Kripnner (1998) on the origins and foundations of the system theory, we try to conceptualize the very essence of the system in the following paragraphs.

To contextualize the idea of "*system*" into the framework of the education at large, and sport education in particular, it is necessary to carry out some considerations about its definition. The "*system*" concept can be formalized, in its broadest picture, as a not defined number of components (characteristic that enable its "*reduction to components*") interacting together (characteristic enabling its "*reduction to dynamics*") and operating within boundaries that ensure the maintenance of both entity and process.

The identification of boundaries, an essential prerequisite in the general system theory, can be difficult to achieve in some fields of human sciences, as sociology and psychology, where number of interactions incessantly shape the behaviours of number of systems components exposed to forces and events outside any possible definition of boundaries. The difficulties arising from that criticism will be dealt with later on.

In the field of biological sciences the general system theory enriches the "*reduction to components*" strategy with the "*reduction to dynamics*" strategy. The "*reduction to component*" applies to the basic question of whether "*the properties, concepts, explanations, or methods from one scientific domain (typically at higher levels of organization) can be deduced from or explained by the properties, concepts, explanations, or methods from another domain of science (typically at lower levels of organization)*" (in Brigandt and Love, 2008). The "*ontological reduction*" (Rosemberg, 2006) supports the idea that each particular biological system is only constituted by molecules and the interactions among molecules. The "*whole*" is, then, mostly the sum of its constituent parts. In the same line of thought, the "*methodological reduction*" supports the idea that the very essence of biological systems lies in its lowest and smallest possible levels, and that experimental studies should be aimed at exploring the underpinning molecular and biochemical structures of any system (Andersen 2017).

Both the heuristic approaches "*reduction to components*" and "*reduction to dynamics*" are aimed at simplifying the too complex set of phenomena characterising all systems of our perceptible and non-perceptible world. Such a simplification is necessary to "*make order out of chaos*", for chaos is often perceived as the leitmotiv of nature. Worster (1990) goes so far as to declare: "*What is there to love or preserve in a universe of chaos? How are people supposed to behave in such a universe?*" Then, the "*reduction to component*" is seen as the only way to re-orient chaos into order, through the inventory and study of the smallest component of any system. In this regard, the Latour's (1983) claim is paradigmatic: "*Give me a laboratory and I will raise the world*".

The heurist approach, alternative to the "*reduction to components*" is then the "*reduction to dynamics*". The study of the smallest component of a system cannot take into account both the behaviours of each component, when subjected to the influence of external factors, and the emerging properties, that come to light when proceeding from a lowest to the highest level of organisation. In this regard, Laszlo and Kripnner (1998) say: "*Structurally, a system is a divisible whole, but functionally it is an indivisible unity with emergent properties. An emergent property is marked by the appearance of novel characteristics exhibited on the level of the whole ensemble, but not by the components in isolation. There are two important aspects of emergent properties: first, they are lost when the system breaks down to its components — the property of life, for example, does not inhere in organs once they are removed from the body. Second, when a component is removed from the whole, that component itself will lose its emergent properties — a hand, severed from the body, cannot write, nor can a severed eye see. The notion of emergent properties leads to the concept of synergy, suggesting that, as we say in everyday language, the system is more than the sum of its parts.*"

This concept became particularly clear in case, for instance, of team sports. A single player, severed out from his team, cannot display the same properties showed by this same player when he is playing as part of the whole represented by his team.

For the primary purposes of our approach, according to Mesarovic and Takahara (1975), we could try to summarize the main goal of the General System Theory as an attempt to explain phenomena in terms of relationships and transformation of components of a system, regardless the specific nature of the system itself. The nature of the mechanism involved (physical, biological, social, etc.) is, then, less explicative than the "*formal relationships between observed features or attributes*" (Mesarovic and Takahara, 1975).

The systems theory offers a trans-disciplinary framework for the study of several aspects of social and education sciences seen as "*relationships between observed features or attributes"*. The studies on cognitive development - defined as the process by which human beings acquire, organize, and learn to use knowledge – and human perception – defined as the way the information conveyed by our sensory organs is organized, interpreted, and filtered through consciousness -, are relying more and more on the systems approach.

von Bertalanffy (1968) anticipated the general tendency leading to the integration of natural and social sciences through the general theory of systems, as well as the possible, and much-needed, integration in scientific education. All this opens the door to an integration between this theory and educational sciences at large.

Without any doubt, the Integral Thinking and the Integral Education concepts derived the foundation of their respective line of thought from the General System Theory, even though not always correctly understood. Galifa (2019), quoting Wilber (2006), preconizes an advanced modality of thinking being independent from any religious or philosophical tradition, maintaining, in the meantime, the possibility of being recognisable by any cultural tradition of the world. In this context, it is not matter of founding a new "*Esperanto*" in terms of thinking system and thinking theory, as the plurality of approaches to the interpretation of our world, in the widest meaning of the term, is the real wealth of the humanity.

The General System Theory is not a way to reduce all thinking to a single interpretative scheme. It is, on the contrary, a way to overcome the dichotomy "*mechanism versus vitalism*" (von Bertalanffy, 1952) or "*holism versus reductionism*" (Koestler, 1970). Whatever way we wish to define such a dichotomy, it is undoubtedly daughter of the Cartesian approach to scientific thought, then it is contextualized inside the western scientific thought.

According to Weckowicz (2000), one of the most important legacies of the General System Theory is the rejection of reductionism and vitalism and the stress on creativity and organized complexity of human behaviours. The human culture makes human unique and different from animals, despite the many essential biological features we share with them. Man is the only living organism able to live in a world of symbols, or rather in worlds of symbols, interposing symbols between himself and the physical objects populating the perceptible world. The most appropriate designation of man is then "*homo symbolicus*".

Taking all this into account, it is clear that the General System Theory, apart from the original and specific biological field for what it has been conceived, and according to the theorists who codified such an approach (Boulding, 1956; von Bertalanffy, 1952; Koestler, 1970), can be useful in number of applications, education strategies included.

Floyd (2008) observed that, since the pioneering works of von Bertalanffy during the 1960s, the so called systems thinking was mature enough to explore disparate domains of inquiry, outside the highly specialised fields from which it emerged and was theorized. The same author is keen to differentiate system thinking from system theory, highlighting those systems thinking is, above all, an epistemology, while the system theory is a representational tool established on ‘four basic ideas: emergence, hierarchy, communication, and control’ (Chichester, 1981 quoted in Floyd, 2008). In our opinion, a correct schematization of the system theory should not omit a fifth basic idea: the boundaries, a fundamental element without which a system simply cannot exist.

It is somewhat surprising that some theorists of the Integral Education did not mention in their works the founders of the “*integral way of thinking*”, just mentioned above. Murray (2009), admitting that “*integral education*” means more than the sum of various theories (concept derived from von Bertalanffy’s work), defines as “*integral*” the meeting point of four perspectives: model, methodology, community and capacities. According to this author, model can be defined as “*system of concepts for interpreting the world*”. In this case, one of the most peculiar characteristics of the model, as conceptualized in the General System Theory is lost. We are referring to the definition of the “*system boundaries*”, an assumption of paramount importance in the analysis of the system dynamics.

Even the concept of holism, as interpreted by Murray (2009), seems to have lost its richness of potentiality to explore the space of human thinking, for this author defines it as:

Holism: An acknowledgement and appreciation of the "*whole person*" or "*whole child*" – mind, body, heart, spirit, and community are all interconnected and important. Artistic expression, bodily movement and health, spontaneity and fun, interaction with the natural world, and service are as important to creating good citizens and realizing students' full potential, as is the learning of "*content*." The physical arrangement of the classroom, what a student had for breakfast, and whether he has caring parents seeing him out the door, all affect his learning and engagement.

This definition reduces the space of interaction to those related to individual, shadowing, in some way, the holonic nature of all that is interacting with him.

Nevertheless, as underlined by Floyd (2008), the transition from the general system dynamic theories to integral thinking and integral education has to solve a specific problem, for the formers explicitly expound the observer from the boundaries of the system observed. In other words, such theories have “*a strongly objectivist stance*” (Floyd, 2008), as “*they are not designed to take account of the relationship between those studying the system and the understanding that their study creates*” (Midgley, 2000). In the sociological/educational field, all this is an evident drawback. In addition, this peculiar field is hard to compare with biological systems as, according to the theorists of deconstructivism/postmodernism the “*meaning is context dependent and contexts are boundless*” (Floyd, 2008).

Accepting the boundless nature of contexts, the foundation of the integral thinking on the general system dynamics theories has to face a sort of epistemological problem: how to find the dynamic analysis of interacting objects within a system without defining the boundaries of the system? Such an impasse is probably more theoretical than practical, in the sense that some specific fields could escape from that bottleneck by focusing on bounded sub-systems of boundless systems. The sport education, operating in the specific context of sport discipline, could, in that sense, consider defining the boundaries of its applicative domain by taking into account the specific nature of sport team. A team, then, could be dealt with as a bounded system pertaining to a boundless social context. Even though such an approach could be considered as forcefully approximate, in reality represents an operational choice able to overcome an otherwise paralyzing cul-de-sac.

According to Murray (2009), the term "*integral*" coupled with education, or even more generally with pedagogy, points out four interrelated points:

- *model* (intended as a system of postulates, data, and inferences presented as a description of an entity or entities of the real world)
- *methodology* (intended as a body of methods, rules, and self-evident basis for reasoning employed by a discipline)
- *community* (intended as a group or groups of people to which integral models and methods is to be applied),
- *capacities* (intended as a developmental stage of thinking able to compromise past modern and post-modern cultural perspectives, and past formal operational modes of thinking).

All of these points, considering the peculiar field of sport education could benefit of the "*integral*" approach in the broadest meaning of the term. It is now mattered to shift from the widely shared constructivist and integral approaches to a paradigm able to merge different learning model into a general system, keeping, in the meantime, all the peculiarities of each model.

HOLONIC APPROACH IN SPORT EDUCATION

The term holon denominates entities displaying at the same time autonomous behaviours, cooperation and synergism. Uliero et al. (2001) points out the importance of balancing of the possible contradictory forces driving each of these properties on a behavioural level. As observed by Calabrese et al. (2011), in this kind of "*cooperation in autonomy*" is rooted the property of "*emergence*", as in complex systems we witness the emergence of characteristics that cannot be deduced from the lower levels of organization.

According to Wilber (2000), the holonic approach is much more than an interpretation of recurring patterns within a systemic dynamic, which is made possible thanks to the interaction among holons. This author states that: "*In all of these movements and more, we see the radiant hand of vision-logic announcing the endless networks of holonic interconnection that constitute the very fabric of the Kosmos itself.*"

Taking apart the possible interpretation of the intimate cosmos structure, the holonic theory is a very useful tool for the analysis of the "…*fields within fields, patterns within patterns, contexts within contexts, endlessly*" (Wilber, 1996) that made the very fabric of nature, social fabric included.

Wilber (2000) describes the holonic nature of our world as follows: "*In other words, we live in a universe that consists neither of wholes nor of parts, but of whole/parts, or holons. Wholes do not exist by themselves, nor do parts exist by themselves. Every whole simultaneously exists as a part of some other whole, and as far as we can tell, this is indeed endless. Even the whole of the universe right now is simply a part of the next moment's whole. There are no wholes, and no parts, anywhere in the universe; there are only whole/parts*."

This is the ground on which the concept of holarchy has been founded. According to Koestler (1967), the concept of hierarch vs that of holarchy can be summed up in Table 1.

Holarchy implies recognizing that every agent in our world, irrespective to their level of organisation, are part of a whole co-evolving with the parts of which it is composed. This co-evolution process incessantly creates and reshapes meanings making. All this, translated in meaningful behavioural patterns, make us to relay on self-affirmation (as holons) and integration (again as holons) making our collective participation and support beneficial for the whole as well as for the individual.

This is particularly true in the team sport dynamics and perfectly apply to sport didactic. In Figure 2 (Bell et al. 1996) another graphic conceptualization of holarchy is reported, where holons and cluster of holons show bidirectional interactions, networking, contemporary multiple states of interaction in a de-centred structure.

Table 1. Hierarchy vs Holarchy

Hierarchy	**Holarchy**
Top-down control. Individuals at higher levels play the role of controllers of the behaviours of individuals at lower levels.	Bidirectional interactions. Lower holons influence higher holons and vice versa.
Linear chain of command. Individual at higher levels rule individual at lower levels in a sequential order.	Networking. Holons can organize in networks resulting in holarchic complex relationships.
Fixed Roles. Individuals in institutional hierarchies are defined by particular functions they fulfil in the organization.	Contemporary multiple states. Holarchies display different kinds of interactions among holons.
Centred structure. Structure or system orbiting around a stable centre. The evolution of such a structure implies the destruction of the gravitational centre and the emergence of a new one.	De-centred structure. Structures that are constantly being re-centred sequentially at a series of locations, like a football game. The focus of activity is ever shifting to something else that was not the focus (Derrida, 1967).

The graphical conceptualisation of hierarchy and holarchy is reported in Figure 1.

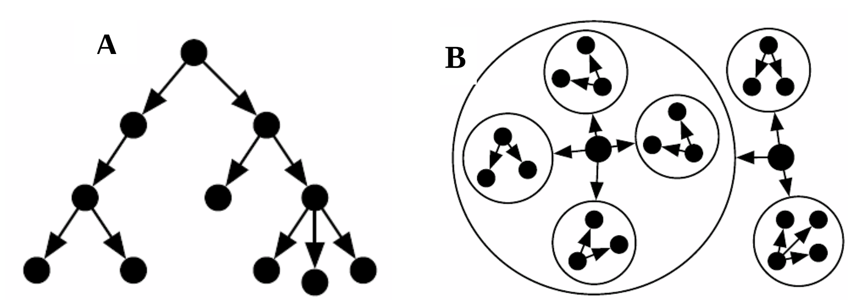

Figure 1. Hierarchical (A) vs holarchical (B) organization (Horling and Lesser, 2005).

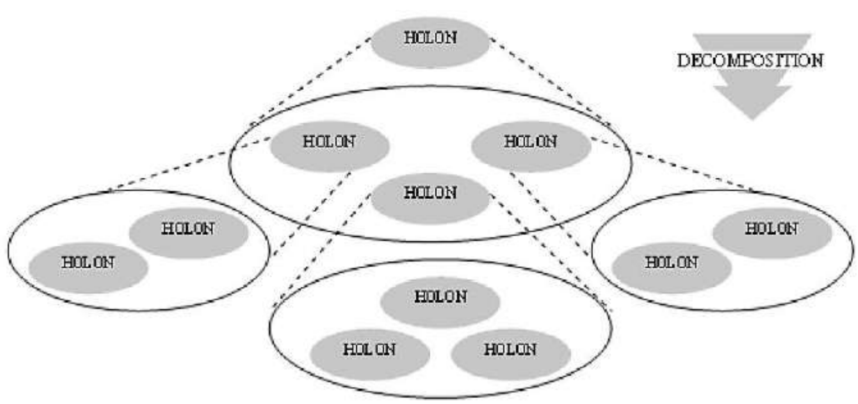

Figure 2. The Bell et al. (1996) graphic conceptualization of holarchy (Georges 2009).

Georges (2009), points out some emergent characteristics of a holarchy of auto-regulated holons:

- Working as autonomous wholes in supra-ordination of their parts;
- Working as dependent parts in subordination of upper control levels;
- Working in coordination with its local environment (other holons and external environment).

Taking into account a bounded system (for instance a sport team), one of its emerging characteristics could be represented by the number of interactions between elements in the evolution within such a system. On the other hand, a complex system, even though is displaying a high number of connections, is not necessarily efficient. A higher efficiency of the system is attained aggregating elements (holons) in clusters interacting each other. This concept is clearly sketched in Figure 3 (Georges, 2006). On the left side of this Figure we found a "*modular system*" where each module (holon) may be largely in control of its own operation and deciding when it communicates with other modules (holons). In this case, the relationship between the elements of the subsets is larger than the relationship between the subsets for all levels. On the right side of Figure 3 we found a model made by three clusters of two sub-clusters, each made of two holons. This configuration, as mathematically demonstrated by Toulouse and Bok (1978), decreases the degree of difficulty (i.e. the number of interactions among modules), stabilizes and makes more efficient the system.

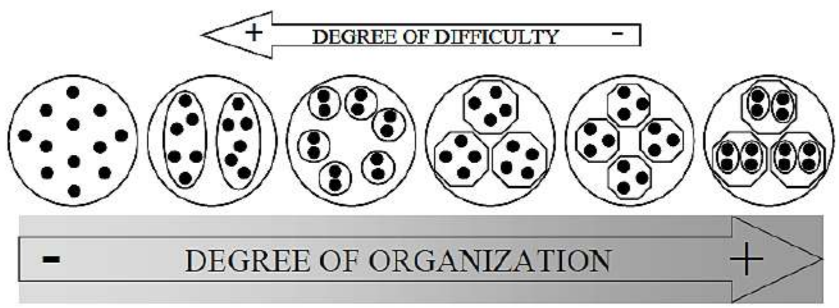

Figure 3. Model of different organizations of a system as function of the degree of clustering of their constituent modules (Georges, 2009).

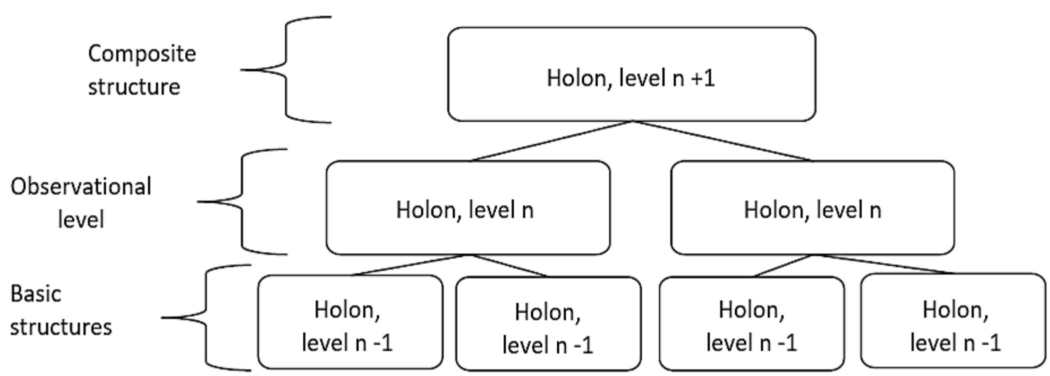

Figure 4. Holon as a centre of relationships with basic components (below ordered) and composite (above ordered) structures (from Mella, 2005).

Interestingly, each group of agent has attributes arising from other agents members of the group, but original and distinct from them. Reasoning from a lower level to a higher level of complexity, a group behave exactly as the single agent constituting it, as it contributes to the properties of one or more groups of which it interacts (Horling and Lesser, 2005). The structure of each of these groupings is a basic unit of organization that can be seen throughout the system as a whole.

Mesarovitch et al. () underline that holons of the same level elaborate elements or information coming from the lower level holons. The results are transferred to upper level holons for further processing. The processes going on at the *level n* holons originate from processes originated from the subordinate *level n - 1* holons and configure those of the super ordered holons at *n + 1 level*. A simple way in which holons participate in a making of a complex structure is outlined in Figure 4.

Horling and Lesser (2005), debating about enterprise holonic organisation, pinpoint the importance of choosing the appropriate agents to be embodied in the individual holons. Ulieru et al. (2001), quoting Zhang and Norries (1999), define three different kinds of holons:

- Static holons.
- Resource holons.
- Mediator holon.

In the context of sport science, static holons could be represented by the physical infrastructures (i.e. ball, lines defining the various segment of a playground, doors or baskets, etc.) corresponds to a group of physical objects, or information, in the environment. Resource holons could be the players and the mediator holons could be the referee and the trainer. In Figure 4 a graphical conceptualisation of this notion is reported.

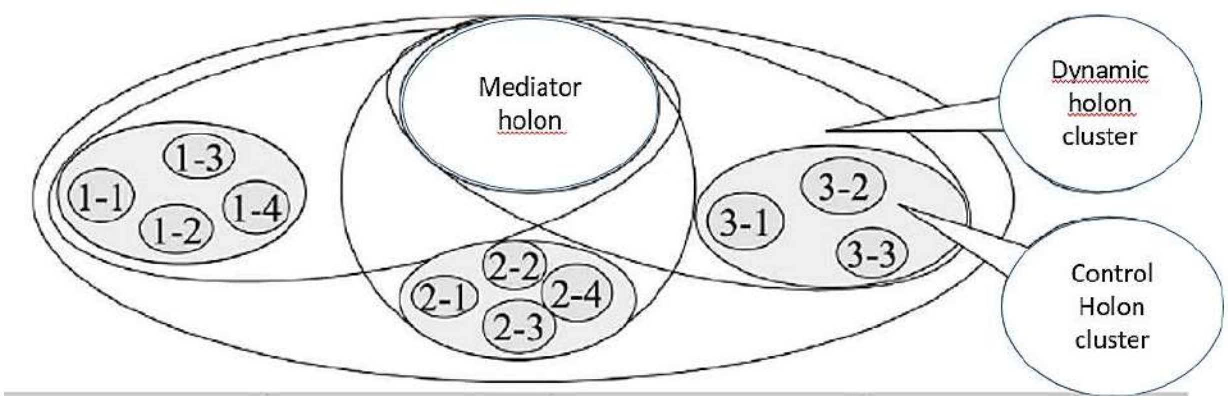

Figure 5. Interrelationships among different holons and holon clusters (modified from Ulieru et al., 2002).

A holonic educational system is, then, a holarchy of collaborative agents oriented towards a common goal. Such agents agglutinates in clusters interacting each other in the view of the optimization of the teaching process.

Holonic systems derive their architecture from the model of autonomous distributed system (Figure 6), since the control is conferred to single peripheral units cooperating through a coordination agent.

The scheme of Figure 6 shows the interplay between players of a hypothetical team sport and a "*coordinator*" (a coach, for instance). A common goal to achieve is essential for obtaining both coordination and cooperation within the system. Such a common goal leads the different elements of the system towards coordinated actions required to fulfil needs emerging from an ever changing environment. The supplementary parameters involved are a) the feeling of belonging to a team and b) the perception of equifinality of the system. The principle of equifinality, according to von Bertalanffy (1950), can be defined as the multiple ways trough which an equilibrium can be approached, even taking the move from different starting points.

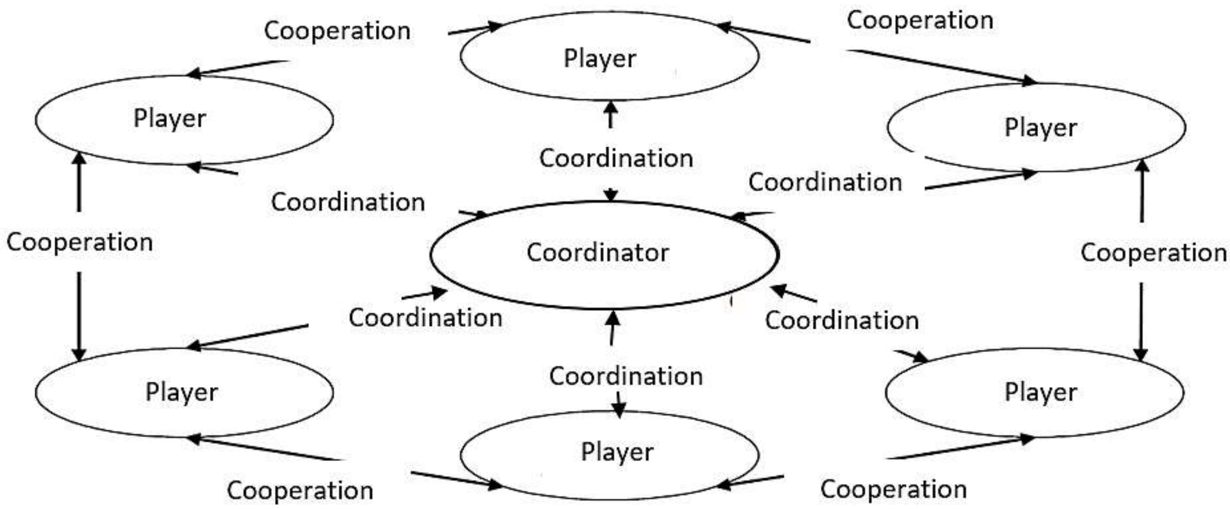

Figure 6. Architecture of a distributed autonomous system applied to a sport team (see text for details). (Modified from Dominici, 2008).

Such a scheme can be easily introduced to sport education, instilling in the pupils the concepts of "*equifinality*", "*common goal*" and the holonic structure of a sport team, leading to a coordinate action deriving from independent holons. The ultimate scope is, then, to integrate systemic creativity into tactical training, through the application of holonic thinking.

Modern team sports require great adaptability and tactical flexibility, characteristics that naturally emerge in self-organized and distributed systems (Cusano et al.,2019). Collective tactical intelligence manifests when players, while maintaining a degree of autonomous decision-making, dynamically cooperate to achieve a common goal. This type of organization is not purely hierarchical but holarchic, where information and tactical decisions emerge through distributed interactions among player-holons (McGarry et al., 2002). In this context:

- Teams with higher collective intelligence tend to dominate the game, as each player contributes to the team's dynamic organization.
- Tactical adaptability is essential to outmanoeuvre opponents, as it allows players to adjust strategies in response to in-game conditions without waiting for external instructions.

One of the most striking examples of emergent collective tactics is the "*tiki-taka*" model adopted by Barcelona and the Spanish national football team (Lago-Peñas et al., 2010). In this style of play, players do not follow rigid schemes but instead continuously adapt, constructing fluid actions through coordinated movements and a dense network of passes. Integrating systemic creativity into tactical training requires a different methodological approach, one that promotes situational learning and real-time decision-making. To this end, several innovative training models have proven effective:

- Tactical Games Approach (TGA) → A method that emphasizes decision-making and game understanding, reducing the emphasis on rigid schemes (Hastie et al., 2025).

- Small-Sided Games → Game simulations on reduced fields to increase player interactions and improve tactical perception (Travassos et al., 2013).
- Constraints-Led Approach → Introducing restrictions in play (e.g., a limited number of touches) to stimulate creativity and strategic adaptation (Renshaw et al., 2010).

All these approaches would greatly benefit from the integration with the holonic theory, which could result in enhancing team's adaptability and game fluidity, preventing the risk of tactical rigidity and distributing responsibilities, activities, and the overall understanding of the ever-changing scenario in which players are called to play. Another interesting issue is that the "*holonic players*," acting in the framework of a the holonic team, could move forward the ability of changing and controlling the playing scenario more rapidly than the opponent team can due.

CONCLUSIONS

The future of tactical training in team sports is moving toward an increasing integration of data analysis and artificial intelligence. Today, many professional clubs are adopting models based on pass network analysis to optimize ball circulation and improve tactical efficiency, such as expected goals statistics (Cusano et al.,2020).

With match analysis driven by AI algorithms, coaches can:

- Analyse recurring game patterns.
- Identify areas for improvement in player connectivity.
- Optimize tactical strategies based on real-time data collection.

These developments align perfectly with holonic theory, which views teams as adaptive complex systems, where learning and tactical evolution are not imposed rigidly from above but emerge through player interactions. The application of holonic thinking and systemic creativity in collective tactics opens new perspectives for sports training. The shift from hierarchical models to self-organized and interconnected structures enables teams to develop greater flexibility, creativity, and adaptability to the dynamic nature of the game. Integrating innovative methodologies such as the Tactical Games Approach, Small-Sided Games, and data analysis improves decision-making and game fluidity, making training more effective and aligned with the modern demands of professional sports. As Koestler (1970) suggested, the future of collective tactics does not rely solely on rigid, predefined schemes but on a dynamic and intelligent system, where each player is an autonomous unit capable of significantly contributing to the team's collective intelligence.

This article does not claim to build a holonic theory of the teaching of sport science through the complete definition of educational mechanisms, structures and processes. Our aim is to underline the undeniable potential of the holonic interpretation of sport teaching, through an examination of its theoretical assumptions and of the links that exist between this theory and other accredited educational paradigms in this field. A more complete operational definition, through the identification of specific educational strategies, which allows the complete implementation of the holonic theory applied to sport teaching is a fruitful field of research to be carried out.

AUTHOR CONTRIBUTIONS

Conceptualization: P.C. and S.D.; Methodology: P.C.; Formal Analysis: P.C. and M.A.J.; Resources: P.C. and M.A.J.; Data Curation: P.C. and S.D.; Writing–Original Draft Preparation: P.C.; Writing–Review & Editing:

P.C.; Visualization: P.C. and M.A.J.; Supervision: P.C. and S.D. All authors have read and agreed to the published version of the manuscript.

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REVIEW ARTICLE

Effect of Vitamin D on athletic performance: A systematic review

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ABSTRACT

Vitamin D is essential for optimal athletic performance; however, the evidence for its effect on athletic performance remains inconclusive. This systematic review aimed to investigate the effect of vitamin D supplementation on athletic performance in athletes. A comprehensive and systematic search of six electronic databases was conducted in accordance with PRISMA reporting guidelines, using a combination of Boolean operators and MeSH keywords. A total of 13 studies were included in the review. The included studies demonstrated that vitamin D supplementation consistently elevates serum 25(OH)D levels in athletes. A subset of the included studies reported significant improvements in athletic performance following the administration of vitamin D supplements, particularly in those athletes with low vitamin D status initially. Another cluster of studies focused on the effects of vitamin D supplementation on parameters of haematological and muscle recovery, with mixed results. Additionally, there were observations of seasonal fluctuations in vitamin D levels, which highlight the importance of considering the timing of supplementation. Vitamin D supplementation has been linked to improved athletic performance, particularly in athletes with low initial vitamin D status. However, the impact of this intervention is influenced by individual characteristics, the type of exercise, and the specific dosage and duration of supplementation. To gain a more comprehensive understanding of the mechanisms and optimal protocols for vitamin D supplementation in athletes, further research is required.
Keywords: Vitamin D, Athletic performance, Supplementation, Systematic review, Athletes.

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INTRODUCTION

Researchers and clinicians have long been interested in understanding the complex relationship between diet and exercise outcomes, particularly the intricate connection between nutrition and athletic performance (Holick et al., 2011). Micronutrients have garnered significant attention in this context, as even small excesses or deficiencies can greatly impact sports performance (Książek et al., 2019). Among these, vitamin D—a fat-soluble secosteroid hormone—stands out as crucial for maintaining normal physiological function. It plays a key role in immune system performance, musculoskeletal health, and overall well-being (Bikle, 2009; Wiciński et al., 2019).

Vitamin D is a crucial regulator of calcium metabolism, essential for maintaining muscle strength, power, and endurance (Trybek et al., 2018). It also plays a fundamental role in modulating muscle function (Lai & Fang, 2013). The vitamin D receptor, a nuclear receptor present in various tissues including skeletal muscle, regulates the expression of genes involved in muscle growth, differentiation, and function (Grant, 2020; Kopeć et al., 2013). Additionally, vitamin D is implicated in the regulation of inflammatory responses, with its anti-inflammatory properties potentially mitigating oxidative stress and muscle damage associated with exercise (Bezuglov, Tikhonova, Zueva, Khaitin, Lyubushkina, et al., 2019; Michalczyk et al., 2020; Solarz et al., 2014).

Despite its well-established importance for overall health, athletes are particularly prone to vitamin D deficiency, raising concerns about the potential impact of low vitamin D levels on sports performance (Bezuglov, Tikhonova, Zueva, Khaitin, Lyubushkina, et al., 2019; Bezuglov, Tikhonova, Zueva, Khaitin, Waśkiewicz, et al., 2019; Wilson-Barnes et al., 2020). Factors contributing to vitamin D deficiency include insufficient sun exposure, skin pigmentation, geographic location, and inadequate dietary intake (Lai & Fang, 2013; Michalczyk et al., 2020). This deficiency can adversely affect athletic performance by reducing immune system function, increasing the risk of injury, and impairing muscular function (Abushamma, 2022; Bezuglov, Tikhonova, Zueva, Khaitin, Waśkiewicz, et al., 2019; Wilson-Barnes et al., 2020). Collectively, these effects can significantly hinder athletic success.

Despite the growing body of evidence, the precise relationship between vitamin D and athletic performance remains unclear. This is likely due to variations in study design, population characteristics, and outcome measures. To address these gaps in understanding, we aimed to systematically analyse the existing literature to elucidate the connection between vitamin D and athletic performance. In addition, we sought to evaluate the potential effectiveness of vitamin D supplementation as an ergogenic aid for athletes.

MATERIALS AND METHODS

Eligibility criteria

This review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021), which ensure transparency, reproducibility, and methodological accuracy. A PECO (Population, Exposure, Comparator, Outcome) framework was employed to guide the systematic review, facilitating the implementation of a comprehensive and targeted literature search. The population of interest was defined as athletes and individuals who engage in regular physical activity. The variable of interest was vitamin D supplementation, which was categorised according to form and dosage. The comparator groups were either placebo or no intervention. The principal outcome under examination was the performance of athletes, including measures of muscle strength, power, and endurance. Moreover, we investigated the potential moderating effects of age, sex, and athletic level on the relationship between vitamin D and athletic performance. The inclusion and exclusion criteria employed in this review are outlined in Figure 1.

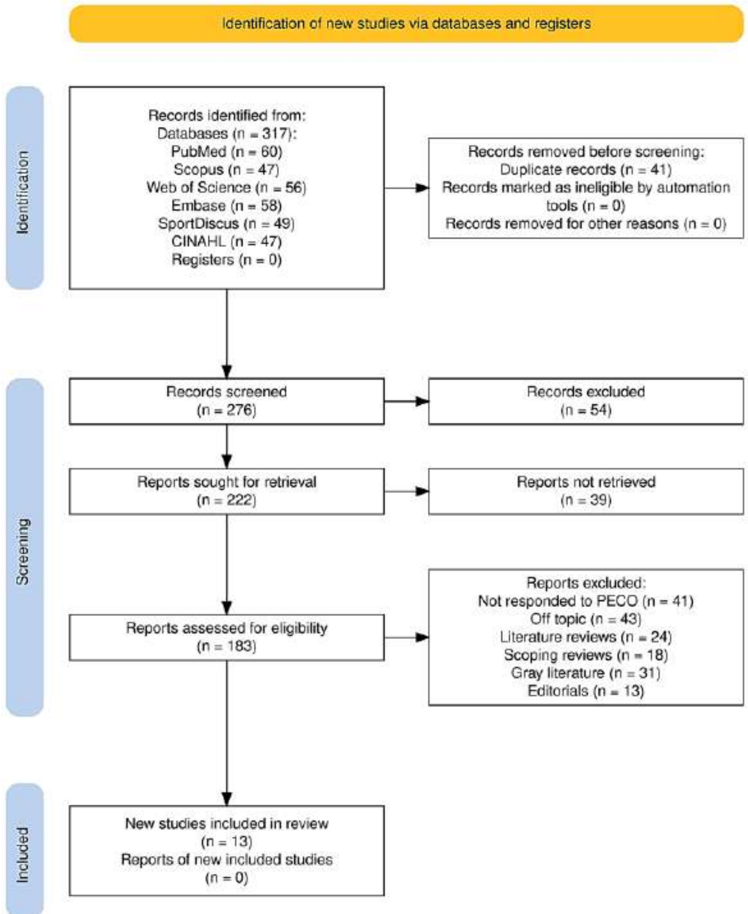

Figure 1. PRISMA protocol representation of the study inclusion process for the review.

Database search protocol

To execute a thorough and systematic review of the literature, we accessed six electronic databases—PubMed, Scopus, Web of Science, Embase, SportDiscus, and CINAHL—employing a mix of Boolean operators and MeSH keywords. Table 1 delineates the search strings utilized across these databases.

Table 1. Selection criteria utilised in this review.

Category	Inclusion Criteria	Exclusion Criteria
Study Design	Randomized Controlled Trials (RCTs), Case-Control Studies	Cross-sectional, Cohort, Observational studies
Population	Athletes, Individuals engaging in physical activity	Non-athletic populations, Sedentary individuals
Intervention	Vitamin D supplementation	Other forms of nutrition or ergogenic aids
Comparator	Placebo or no intervention	Active comparators (other nutrients or supplements)
Outcome	Athletic performance metrics	Other health outcomes (cardiovascular, metabolic, etc.)
Language	English	Non-English language publications
Publication Date	No restrictions	-

Data items extracted
In order to ensure the systematic and thorough extraction of data from the selected studies, a standardised protocol for data extraction was established. Two independent reviewers extracted the data from each study using a form that had been meticulously designed for this purpose. The form was subjected to pilot testing and subsequent refinement in order to guarantee the comprehensive capture of all pertinent data elements.

The data elements selected for analysis were comprehensive and encompassed four principal categories. At the outset, the characteristics of the studies were documented, including authorship, publication year, country of origin, study design, sample size, demographic details of the population (such as age and sex), and the study duration. Subsequently, the characteristics of the interventions were delineated. This included noting the type of vitamin D supplementation, dosage, duration, administration frequency and route of administration. In the third stage, the outcome measures were recorded, with a particular focus on indicators of athletic performance, including muscle strength, power and endurance. Lastly, the methodological rigour of each study was evaluated, with particular attention paid to aspects such as randomisation, allocation concealment, blinding, and adherence to the intention-to-treat principle.

Bias assessment protocol
For the randomized controlled trials (RCTs), we employed the Cochrane Risk of Bias 2.0 tool (Sterne et al., 2019) to evaluate the risk of bias. Conversely, for the non-randomized studies, we applied the ROBINS-I method (Igelström et al., 2021) to assess the risk of bias across multiple domains. This approach enabled us to identify potential sources of bias and assess their influence on the outcomes of the study.

RESULTS

Article selection schematics
The initial phase of our methodology involved identifying relevant records from various sources, including databases and registries, as depicted in Figure 2.

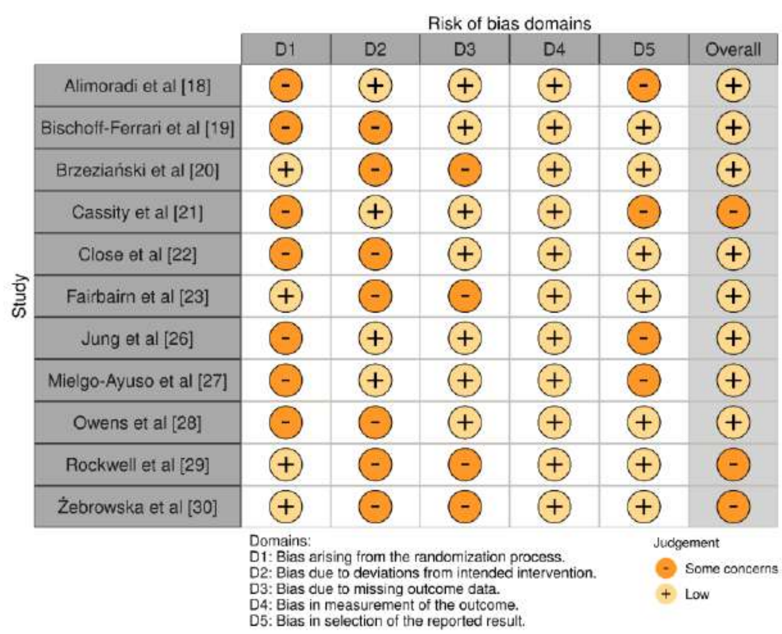

Figure 2. Bias assessment using the RoB 2.0 tool.

Although no records were retrieved from registries, a total of 317 records were obtained from databases. Prior to screening, 41 records were removed due to duplication, with no records excluded for any other reason, leaving 276 records for review.

During the screening phase, each record was meticulously evaluated to determine its relevance to the review. Of the 276 records scrutinized, 54 were excluded due to the unavailability of the full text. Subsequent requests for retrieval resulted in 222 reports being obtained. However, 39 reports remained unretrievable, leaving 183 reports to be assessed for eligibility.

The eligibility assessment involved a detailed review of each report against the PECO criteria. As a result, 43 reports were deemed off-topic, and 41 were excluded for not addressing the PECO criteria. Additionally, 24 literature reviews, 18 scoping reviews, 31 grey literature reports, and 13 editorials were excluded for not meeting the inclusion criteria. Ultimately, 13 trials (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Close et al., 2013; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Owens et al., 2017; Rockwell et al., 2020; Żebrowska et al., 2020) were determined to be eligible and were included in the evaluation.

Assessed levels of bias

The protocol for assessing bias depicted a varied risk of bias across the studies included. Utilizing the Cochrane Risk of Bias 2.0 tool (Figure 3), a substantial number of studies predominantly exhibited "*some concerns*" regarding bias stemming from the randomization process, including studies by Alimoradi et al.(Alimoradi et al., 2019), Bischoff-Ferrari et al.(Bischoff-Ferrari et al., 2020), Cassity et al.(Cassity et al., 2016), Close et al.(Close et al., 2013), Jung et al. (Jung et al., 2018), Mielgo-Ayuso et al.(Mielgo-Ayuso et al., 2018), Owens et al.(Owens et al., 2017), and Rockwell et al.(Rockwell et al., 2020). Additionally, fewer studies demonstrated "*some concerns*" in the domains of bias due to deviations from intended interventions (Bischoff-Ferrari et al.(Bischoff-Ferrari et al., 2020), Close et al.(Close et al., 2013), Rockwell et al. (Rockwell et al., 2020)) and bias in outcome measurement (Alimoradi et al.(Alimoradi et al., 2019), Cassity et al.(Cassity et al., 2016), Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018)).

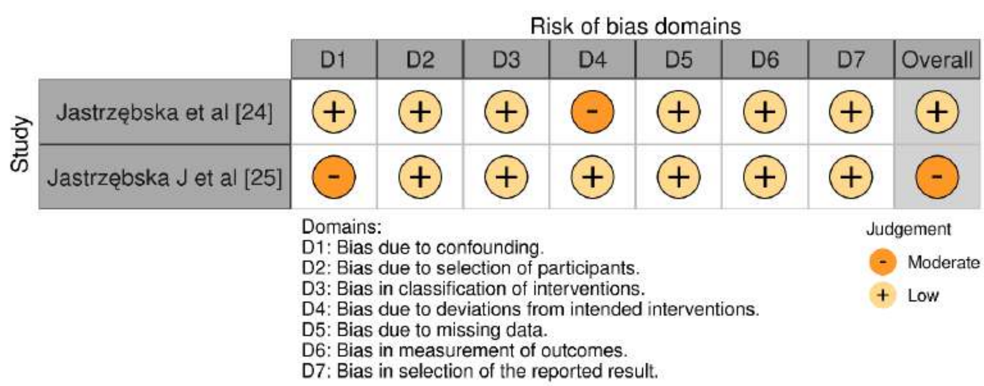

Figure 3. Bias assessment using ROBINS-I tool.

Employing the ROBINS-I tool (Figure 4), the sole non-randomized study by Jastrzębska et al. (Jastrzębska et al., 2018) was evaluated as having a "*moderate*" risk of bias in the domain of confounding, while the risks in other domains were deemed "*low*". A subsequent study by Jastrzębska J et al. (Jastrzębska et al., 2022)was similarly assessed to have a "*moderate*" risk of bias in the domain of confounding.

Baseline characteristics

Table 2 presents a summary of the assessments conducted across all the trials included in this review (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Close et al., 2013; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Owens et al., 2017; Rockwell et al., 2020; Żebrowska et al., 2020). A detailed analysis of the table indicates that the majority of these studies (9 out of 12) utilized a randomized controlled trial (RCT) design, which is recognized as the gold standard for assessing the efficacy of interventions (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Rockwell et al., 2020). Notably, two studies implemented specific designs: one employed a double-blind, placebo-controlled factorial RCT design (Bischoff-Ferrari et al., 2020), and the other a repeated measures design(Owens et al., 2017). Only one study adopted a longitudinal design (Brzeziański et al., 2022). The participant demographics across the studies were quite diverse, covering a range of populations from young soccer players (Brzeziański et al., 2022; Jastrzębska et al., 2022; Jastrzębska et al., 2018) to collegiate swimmers and divers(Cassity et al., 2016), professional rugby players(Fairbairn et al., 2018), elite male rowers (Mielgo-Ayuso et al., 2018), and endurance runners (Żebrowska et al., 2020). The sizes of the study samples also varied significantly, from as few as 19 participants (Rockwell et al., 2020) to as many as 2157(Bischoff-Ferrari et al., 2020). Most studies targeted athletes who exhibited low levels of vitamin D or were at risk of deficiency (Alimoradi et al., 2019; Jung et al., 2018).

Table 2. Search phrases utilised across the databases.

Database	**Search string**
PubMed	(vitamin D OR cholecalciferol OR ergocalciferol) AND (athletic performance OR exercise performance OR physical performance) AND (randomized controlled trial OR RCT OR controlled clinical trial OR case-control study)
Scopus	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic performance OR exercise performance OR physical fitness) AND (article OR review OR conference paper) AND (English language OR language: English)
Web of Science	(vitamin D* OR cholecalciferol* OR ergocalciferol*) AND (athletic perform* OR exercise perform* OR physical perform*) AND (article OR review OR proceeding paper) AND (English language OR language: English)
Embase	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic performance OR exercise performance OR physical fitness) AND (human OR human studies) AND (English language OR language: English)
SportDiscus	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic perform* OR exercise perform* OR physical perform*) AND (human OR human studies) AND (English language OR language: English)
CINAHL	(vitamin D OR vitamin D2 OR vitamin D3) AND (athletic performance OR exercise performance OR physical fitness) AND (research article OR journal article OR peer-reviewed) AND (English language OR language: English)

Parameters and outcomes assessed

Alimoradi et al. (Alimoradi et al., 2019)explored the effect of vitamin D supplementation on the athletic performance of Iranian athletes. Their findings indicated that an 8-week regimen of weekly vitamin D supplementation, at a dose of 50,000 IU, significantly increased circulating 25(OH)D levels and improved performance in athletic tests. In a separate study, Bischoff-Ferrari et al. (Bischoff-Ferrari et al., 2020) conducted a large-scale, double-blind, placebo-controlled trial to assess the effects of omega-3 fatty acids, exercise, and vitamin D3 on various health outcomes in elderly individuals. The results demonstrated that daily administration of 2000 IU of vitamin D3 over three years significantly enhanced blood pressure, and physical function, and reduced the incidence of infections and nonvertebral fractures.

Brzeziański et al. (Brzeziański et al., 2022) investigated the effects of vitamin D supplementation on the exercise performance of young soccer players. The study found that administering 20,000 IU of vitamin D twice weekly over eight weeks improved sprint testing, explosive power, VO2 max, and 25(OH)D levels. Similarly, Cassity et al. (Cassity et al., 2016) explored the influence of daily vitamin D3 supplementation on bone turnover markers, body composition, and 25(OH)D levels among collegiate swimmers and divers. Their findings indicated that 4000 IU of vitamin D3 daily for six months significantly increased 25(OH)D levels and reduced bone turnover indicators.

Table 3. Studies included in the review and their observed assessments.

Study	Design & Participants	Interventions	Duration	Primary Outcomes	Key Results	Overall conclusion observed
Alimoradi et al.	Randomized controlled trial; 70 Iranian athletes	Weekly Vitamin D (50,000 IU) vs. placebo	8 weeks	Circulating 25(OH)D, athletic performance tests	25(OH)D: D group +17.3 ± 16.9 ng/mL, $p < .001$; P group -3.1 ± 8.4 ng/mL, $p = .040$ Performance: Significant improvement in leg press ($p = .034$) and sprint ($p = .030$) in D group	Weekly 50,000 IU Vitamin D increased 25(OH)D by ~17 ng/mL, improving power leg press and sprint performance.
Bischoff-Ferrari et al.	Double-blind, placebo-controlled factorial RCT; 2157 older adults	Vitamin D3 (2000 IU/day), omega-3s (1 g/day), exercise, placebo	3 years	BP, SPPB, MoCA, nonvertebral fractures, infection rates	BP: No significant change (e.g., Systolic BP: -0.8 mm Hg, $p < .13$) Infections: Omega-3s reduced IR by 0.13, ratio 0.89 ($p = .02$) Other outcomes: No significant changes	No statistically significant benefits of Vitamin D3, omega-3s, or exercise alone or combined on primary outcomes over 3 years.
Brzeziański et al.	RCT; 25 young soccer players	Vitamin D (20,000 IU twice/week) vs. none	8 weeks	25(OH)D, VO2max, sprint tests, explosive power	25(OH)D: GS + ($p = .002$; ES = 0.36) VO2max: GS + ($p = .031$) Explosive Power: Insignificant ($p = .07$)	Vitamin D supplementation improved VO2max in young soccer players but had a trivial effect on explosive power.
Cassity et al.	RCT; 32 collegiate swimmers and divers	Vitamin D3 (4000 IU/day) vs. placebo	6 months	25(OH)D, bone turnover markers, body composition	25(OH)D: BMI - correlated with 6-month change (R = -0.496; $p = .03$) Bone turnover: High turnover = greater 25(OH)D loss ($p = .03$)	Normal BMI athletes showed a diminished response to vitamin D3; high bone turnover may compromise vitamin D status.
Close et al.	RCT; 30 club-level athletes	Placebo, 20,000 or 40,000 IU/week vitamin D3	12 weeks	25(OH)D, 1-RM bench press, leg press, vertical jump	25(OH)D: Increased in all (e.g., 20,000 IU: 79 ± 14 nmol/l at 12 weeks) Performance: No significant effect ($p > .05$)	Vitamin D3 supplementation increased serum levels but did not improve physical performance measures.
Fairbairn et al.	RCT; 57 professional rugby players in New Zealand	50,000 IU cholecalciferol (3,570 IU/day) vs. placebo	11-12 weeks	25(OH)D, 30m sprint, weighted reverse-grip chin up	25(OH)D: +32 nmol/L vs. placebo ($p < .001$) Performance: No difference except in chin up (+5.5 kg, $p = .002$)	Vitamin D significantly increased serum levels but had minimal impact on performance, except in chin-up strength.
Jastrzębska et al.	RCT; 36 soccer players undergoing HIIT	Vitamin D supplementation vs. placebo	8 weeks	25(OH)D, PWC170, lactate threshold (LT), VO2max	25(OH)D: SG +119%, PG -8.4% VO2max: SG +20%, PG +13% LT Velocity: Similar in both groups	Vitamin D showed a moderate positive impact on aerobic capacity in soccer players.
Jastrzębska J et al.	Longitudinal study; 24	Vitamin D supplementation vs. placebo	1 year	25(OH)D, Ca, P, PTH, aerobic	25(OH)D: Highest in summer (T1: 94 nmol/L, T4: 94 nmol/L)	Vitamin D levels fluctuated seasonally; supplementation did

	young soccer players			capacity, speed, power	Aerobic Capacity: Significant time x group effect	not have a sustained effect on 25(OH)D levels.
Jung et al.	RCT; 35 collegiate TKD athletes with low 25(OH)D	Vitamin D3 (5,000 IU/day) vs. placebo	4 weeks	25(OH)D, Wingate test, isokinetic strength, CMJ, sit-ups, agility, 20 m pacer	25(OH)D: VD + (96.0 ± 3.77 nmol/L), PG no change (F = 242.44, *p* = .000) Performance: Significant for anaerobic peak power (F = 7.49, *p* = .010) and isokinetic knee extension (F = 6.08, *p* = .019)	Vitamin D3 improved some aspects of performance, but not all, in TKD athletes with low 25(OH)D levels.
Mielgo-Ayuso et al.	RCT; 36 elite male rowers	Vitamin D3 (3000 IU/day) vs. control	8 weeks	Haematological and iron metabolism, testosterone, cortisol	25(OH)D: VD3G + (26.24 ± 8.18 to 48.12 ± 10.88 ng/mL, *p* < .001) Haemoglobin: CG -2.89 ± 2.29%, VD3G +0.71 ± 1.91% (*p* = .009) Haematocrit: CG -1.57 ± 2.49%, VD3G +1.16 ± 1.81% (*p* = .019)	Vitamin D3 supplementation improved haematological parameters but did not significantly enhance muscle recovery.
Owens et al.	Repeated measures; 46 elite European athletes	Vitamin D3 (35,000 or 70,000 IU/week)	12 weeks	Vitamin D metabolites, PTH levels	25(OH)D: Both doses + PTH: Decreased by week 6 70,000 IU: Increased 24,25[OH]2D (*p* < .05)	High-dose vitamin D3 may be detrimental due to increased 24,25[OH]2D; lower, frequent doses are preferable.
Rockwell et al.	RCT; 19 NCAA Division I swimmers	Vitamin D3 (5000 IU/day) vs. placebo	12 weeks	25(OH)D, body composition, strength/power, anabolic hormones	25(OH)D: VITD +8%, PLA -44% Fat-free mass: VITD + (56.4 to 59.1 kg, *p* < .05) Strength/Power: Significant for dead lift (F = 21.577, *p* < .01) and vertical jump (F = 11.219, *p* < .01)	Vitamin D supplementation maintained 25(OH)D levels and enhanced fat-free mass and some strength/power aspects.
Żebrowska et al.	RCT; 24 endurance runners	Vitamin D (2000 IU/day) vs. placebo	3 weeks	25(OH)D, muscle biomarkers (troponin, myoglobin, CK, LDH)	25(OH)D: VD + (40.3 ± 4.9 ng/mL), PL - (31.8 ± 4.2 ng/mL) Biomarkers: VD reduced post-exercise troponin, myoglobin, TNF-α, and CK levels	Vitamin D supplementation improved 25(OH)D levels and reduced muscle injury biomarkers in runners.

Close et al. (Close et al., 2013) investigated the effects of vitamin D3 supplementation on the athletic performance of club-level athletes. The study found that after 12 weeks of supplementation with either 20,000 or 40,000 IU of vitamin D3 per week, there were improvements in 1-RM bench press, leg press, vertical jump, and 25(OH)D levels. Similarly, Fairbairn et al. (Fairbairn et al., 2018) explored the impact of vitamin D supplementation on professional rugby players in New Zealand. Their findings indicated that administering 75-100 IU of vitamin D for 11–12 weeks enhanced 25(OH)D levels, 30 m sprint times, and performance in weighted reverse-grip chin-ups.

Jastrzębska et al. (Jastrzębska et al., 2018)aimed to explore the impact of vitamin D supplementation on exercise performance in soccer players undergoing high-intensity interval training (HIIT). The research revealed that eight weeks of vitamin D supplementation led to significant improvements in VO2max, PWC170, lactate threshold (LT), and 25-hydroxyvitamin D (25(OH)D) levels. In a subsequent longitudinal study, Jastrzębska et al. (Jastrzębska et al., 2022) examined the effects of vitamin D supplementation on the aerobic capacity, speed, and power of young soccer players. The outcomes of this year-long investigation demonstrated that vitamin D administration was associated with enhancements in power, speed, aerobic capacity, and 25(OH)D concentrations.

Jung et al. (Jung et al., 2018) investigated the effects of vitamin D3 supplementation on the physical performance of collegiate Taekwondo athletes exhibiting low serum 25-hydroxyvitamin D (25(OH)D) levels. Their findings indicated that supplementation with 5,000 IU/day of vitamin D3 for four weeks led to improvements in 25(OH)D levels, performance on the Wingate test, isokinetic strength, and counter-movement jump (CMJ) outcomes. Similarly, Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018) explored the effects of vitamin D3 supplementation on hormonal balance and metabolic functions in elite male rowers. The study revealed that 8 weeks of supplementation with 3,000 IU/day of vitamin D3 enhanced levels of cortisol and testosterone, as well as haematopoietic and iron metabolism.

Owens et al. (Owens et al., 2017) investigated the effects of vitamin D supplementation on parathyroid hormone (PTH) levels and vitamin D metabolites in elite European athletes. Their findings indicated that 12 weeks of vitamin D supplementation, at doses of either 35,000 or 70,000 IU per week, significantly improved PTH levels and vitamin D metabolites. Rockwell et al. (Rockwell et al., 2020) explored the influence of vitamin D3 supplementation on anabolic hormones, strength, power, and body composition among NCAA Division I swimmers. The study revealed enhancements in anabolic hormones, body composition, strength, power, and 25-hydroxyvitamin D (25(OH)D) levels following 12 weeks of treatment with 5000 IU of vitamin D3 per day. Additionally, Żebrowska et al. (Żebrowska et al., 2020) examined the impact of vitamin D supplementation on muscle biomarkers in endurance runners. The results demonstrated that a three-week regimen of vitamin D supplementation, at 2000 IU per day, increased levels of 25(OH)D and decreased muscle biomarkers, including myoglobin, troponin, creatine kinase (CK), and lactate dehydrogenase (LDH).

Findings observed

Research conducted by Alimoradi et al. (Alimoradi et al., 2019) found that administration of vitamin D significantly increased 25(OH)D levels and improved athletic performance, notably in leg press and sprint tests. Conversely, Bischoff-Ferrari et al. (Bischoff-Ferrari et al., 2020)observed that omega-3 supplementation reduced the risk of infections, whereas vitamin D supplementation had no significant effect on blood pressure or other measured outcomes. Similar to that Brzeziański et al. (Brzeziański et al., 2022) reported that while vitamin D administration raised 25(OH)D levels and VO2max, it did not significantly affect explosive power.

Cassity et al. (Cassity et al., 2016) identified a negative correlation between BMI and 25(OH)D levels with vitamin D supplementation, noting that greater losses of 25(OH)D were associated with higher bone turnover rates. Meanwhile, research by Close et al. (Close et al., 2013)demonstrated that although vitamin D supplementation consistently increased 25(OH)D levels, it did not yield a noticeable enhancement in sports performance. Fairbairn et al. (Fairbairn et al., 2018) found that vitamin D supplementation not only elevated 25(OH)D levels but also improved performance in chin-up tests, though it showed no significant impact on other performance indicators.

Jastrzębska et al. (Jastrzębska et al., 2018) observed no significant differences in the improvements of 25(OH)D levels, VO2max, and lactate threshold velocity following vitamin D supplementation. Conversely, Jastrzębska et al. (Jastrzębska et al., 2022) noted significant time x group effects attributed to vitamin D supplementation, which enhanced aerobic capacity, anaerobic peak power, and 25(OH)D levels. Jung et al. (Jung et al., 2018) reported a significant positive impact of vitamin D supplementation on performance, evidenced by increased 25(OH)D levels, anaerobic peak power, and isokinetic knee extension strength.

Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018) identified significant group differences in the enhancement of haematological parameters and iron metabolism, specifically haemoglobin and haematocrit, following vitamin D supplementation. Owens et al. (Owens et al., 2017) found that vitamin D supplementation elevated 25(OH)D levels and reduced PTH levels, demonstrating significant effects on vitamin D metabolites at higher dosages.

Rockwell et al. (Rockwell et al., 2020) reported significant improvements in 25(OH)D levels, fat-free mass, strength, and power due to vitamin D supplementation, which also affected performance metrics such as the deadlift and vertical jump. Lastly, Żebrowska et al. (Żebrowska et al., 2020) found that vitamin D supplementation post-exercise led to decreased muscle biomarkers including troponin, myoglobin, TNF-α, and CK levels, while increasing 25(OH)D levels.

DISCUSSION AND CONCLUSION

A comprehensive analysis of the included trials (Alimoradi et al., 2019; Bischoff-Ferrari et al., 2020; Brzeziański et al., 2022; Cassity et al., 2016; Close et al., 2013; Fairbairn et al., 2018; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Jung et al., 2018; Mielgo-Ayuso et al., 2018; Owens et al., 2017; Rockwell et al., 2020; Żebrowska et al., 2020) highlights several trends and connections that elucidate the collective findings. Notably, a consistent increase in serum 25(OH)D levels following vitamin D supplementation was observed in 12 of the 13 studies. This finding suggests that vitamin D status in athletes can be effectively enhanced through supplementation. A specific subset of studies (Alimoradi et al., 2019; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Rockwell et al., 2020) reported significant improvements in power, strength, and aerobic capacity among athletes following vitamin D administration. These athletes presented with low baseline vitamin D levels, and the dosages of supplementation varied between 50,000 and 70,000 IU per week, indicating a pattern across these investigations. In contrast, studies involving athletes with normal initial vitamin D levels or those receiving lower doses of supplementation showed no significant enhancements in performance(Bischoff-Ferrari et al., 2020; Close et al., 2013; Fairbairn et al., 2018).

A subset of studies (Cassity et al., 2016; Mielgo-Ayuso et al., 2018; Owens et al., 2017) focused on the impact of vitamin D supplementation on muscle and haematological recovery metrics. Cassity et al. (Cassity et al., 2016) found no significant effects on muscle recovery, although Mielgo-Ayuso et al. (Mielgo-Ayuso et al., 2018) reported improvements in haematological markers. Owens et al. (Owens et al., 2017) suggested that increased levels of 24,25[OH]2D might render high-dose vitamin D3 supplementation detrimental. These findings underscore the complexity of vitamin D's influence on physiological outcomes and the necessity for further research. Seasonal fluctuations in vitamin D levels were documented by Fairbairn et al. (Fairbairn et al., 2018)and Żebrowska et al. (Żebrowska et al., 2020), emphasizing the importance of timing in supplementation strategies. Additionally, Żebrowska et al. (Żebrowska et al., 2020) demonstrated that vitamin D supplementation could reduce muscle injury biomarkers in runners, potentially influencing injury prevention strategies.

The study conducted by Bischoff-Ferrari et al. (Bischoff-Ferrari et al., 2020), which analysed primary outcomes over a three-year period, did not demonstrate any statistically significant effects from the individual or combined interventions of omega-3 fatty acids, exercise, or vitamin D3. This study is distinguished by its unique methodology and focus on long-term outcomes, setting it apart from other research in the field. Conversely, several studies included in the review (Alimoradi et al., 2019; Jastrzębska et al., 2022; Jastrzębska et al., 2018; Rockwell et al., 2020) present consistent findings, indicating that vitamin D supplementation significantly enhances athletic performance. Another subset of research (Cassity et al., 2016; Mielgo-Ayuso et al., 2018; Owens et al., 2017) primarily investigates markers of muscular and haematological recovery. The remaining studies, which vary in their conclusions and methodologies, exhibit less congruence (Bischoff-Ferrari et al., 2020; Close et al., 2013; Fairbairn et al., 2018; Żebrowska et al., 2020).

Numerous studies (Abushamma, 2022; de La Puente Yagüe et al., 2020; Sist et al., 2023; Wyatt et al., 2024), along with this review, suggest that vitamin D supplementation could be advantageous for health and athletic performance, particularly in athletes with deficient initial levels of vitamin D. There is a continued need for research to determine optimal dosages of vitamin D supplements and their effects on various outcomes, such as bone health, risk of injury, and muscle recovery. Our analysis indicates that vitamin D supplementation consistently elevated serum 25(OH)D levels in athletes; moreover, a subset of studies reported notable improvements in strength, power, and aerobic capacity among athletes with initially low vitamin D levels. Conversely, Abushamma et al. (Abushamma, 2022) highlighted ongoing debates regarding the application of vitamin D supplementation in sports, emphasizing the necessity for further research to establish the ideal dosages for athletes. Wyatt et al. (Wyatt et al., 2024) also found that vitamin D supplementation could enhance elite athletes' strength, anaerobic power, and aerobic endurance; yet, more studies are needed to confirm its benefits on bone health and injury prevention.

Puente et al.'s research (de La Puente Yagüe et al., 2020) highlighted the critical role of vitamin D in bone health as well as its extra-skeletal functions, which influence athletic performance through mechanisms such as skeletal muscle growth, immune and cardiovascular responses, and inflammatory regulation. The study noted that vitamin D interacts with extra skeletal tissues, potentially affecting infection risk and influencing the rate of injury healing. Additionally, a meta-analysis conducted by Sist et al. (Sist et al., 2023)evaluated the effects of vitamin D supplementation on muscle strength and power in athletes. Their findings indicated that while vitamin D supplementation did not alter muscle power in athletes with normal or elevated baseline serum 25(OH)D levels, it did have a modest effect on both upper and lower body muscle strength in athletes with low baseline serum 25(OH)D concentrations.

The findings and conclusions of the studies exhibit considerable variability. For example, our analysis suggests that vitamin D supplementation may influence injury prevention, contrasting with Wyatt et al. (Wyatt et al., 2024), who report inconsistent evidence regarding its effects on bone health and injury risk. Additionally, we found that vitamin D supplementation could be beneficial for enhancing power, strength, and aerobic capacity, whereas Sist et al. (Sist et al., 2023) observed minimal effects on muscle strength and power.

A high prevalence of vitamin D deficiency is noted among athletic populations, with increased risk factors such as higher latitudes, the winter and early spring seasons, and participation in indoor sports (Farrokhyar et al., 2015). The definition of vitamin D deficiency, however, remains a subject of ongoing debate. While current evidence suggests that serum 25(OH)D concentrations below 75 nmol/L might be considered deficient in white male athletes (Ribbans et al., 2021), the relevance of this threshold for athletes from diverse ethnic backgrounds is uncertain. Notably, research indicates that while total 25(OH)D and vitamin D-binding protein (VDBP) levels are lower in black individuals compared to white individuals, the levels of bioavailable 25-hydroxyvitamin D are similar, suggesting that 1,25(OH)D may be a more accurate marker of vitamin D status (Powe et al., 2013). The deficiency of vitamin D has been associated with impaired muscle function, evidenced by proximal muscle weakness and reduced diameter of type II muscle fibres (Ceglia, 2008). Given the strong correlation between muscle function and force-time characteristics (Suchomel et al., 2016), as well as injury incidence (Hootman et al., 2007; Van Mechelen et al., 1992), the impact of vitamin D on muscle strength in athletes has attracted significant research interest. Despite the demonstrated effectiveness of vitamin D supplementation in improving vitamin D status (Farrokhyar et al., 2017), the evidence regarding its effects on maximal strength and power in athletes remains limited and currently inconsistent(Han et al., 2019; Zhang et al., 2019).

Limitations

There are a few caveats to consider when interpreting the results of this systematic study. First off, there's a chance that the varied study designs, populations, and supplementation strategies across the included studies contributed to the diversity in the findings. Furthermore, the bulk of the studies had small sample sizes, which would have reduced the findings' generalisability and estimate precision. Moreover, since the examination was restricted to works written in English, pertinent works written in other languages might have been overlooked. Despite being thorough, the search strategy might have overlooked some pertinent research, especially those that had unfavourable results that are frequently not publicly disclosed. Because the included studies' quality was not properly evaluated, bias may have been introduced into the interpretation of the findings. Finally, while investigating the possible pathways via which vitamin D supplementation may influence athletic performance would have yielded important insights into the physiological processes that underlie the effects, the review did not do so.

Clinical recommendations

The findings of the systematic review yield several recommendations. It can be posited that vitamin D supplementation may enhance athletic performance, in particular among athletes who have initially low vitamin D serum levels. Nevertheless, further research is necessary to ascertain the optimal doses and durations of supplementation. It should be noted that seasonal variations in vitamin D levels have the potential to influence the efficacy of supplementation, underscoring the importance of timing. Therefore, it is recommended that athletes and coaches consider these variations when devising training schedules. Additionally, due to the current lack of conclusive data, further research is necessary to assess the effects of vitamin D supplementation on haematological and muscle recovery metrics. To generate more precise estimations of vitamin D's impact on athletic performance, future research should prioritise high-quality, well-designed trials with large sample sizes.

AUTHOR CONTRIBUTIONS

The authors confirm that all authors have made substantial contributions to all of the following: the conception and design of the study, or acquisition of data, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be submitted; and sound scientific research practice.

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No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

The placebo effect does not enhance sprinting or jumping performance in trained athletes

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ABSTRACT

This study aimed to analyse the placebo effect associated with caffeine on the performance of sprinters in a 60-meter sprint test and a standing triple jump. Methods: Thirteen trained sprinters (7 men, 6 women) volunteered to complete the experimental procedures (22.8 ± 4.7 years, 64.7 ± 6.5 kg and 173.9 ± 6.5 cm). A repeated, randomized, and counterbalanced experimental design was used to compare the effects of the ingestion of a placebo reported as caffeine (placebo) and a control situation where no substance was ingested (control). In both conditions, they completed a standing triple jump, and a 60-meter sprint test and filled out a questionnaire about potential side effects. Results: Performance was similar in placebo and control conditions in the 60-meter sprint test (7.52 ± 0.46 vs. 7.55 ± 0.43 s; *p* = .49; small d = 0.20) and the standing triple jump (7.28 ± 0.84 vs. 7.28 ± 0.87 m; *p* = .95; trivial d = 0.02). The most frequent side effects derived from deceptive caffeine ingestion were increased activeness (53.8%), nervousness (23.1%) and insomnia (15.4%). Conclusion: Deceptive caffeine ingestion did not alter performance in sprint and triple jump performance in trained athletes, while some minor side effects appeared. Individual responses to placebo ingestion should be carefully considered before making recommendations for sprint athletes.
Keywords: Performance analysis, Expectancy, Deceptive administration, Ergogenic aids, Sports performance.

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INTRODUCTION

Placebo effects involve a variety of psychological and physiological mechanisms and could be influenced by situational and learning conditions (Colloca & Barsky, 2020; Frisaldi et al., 2020; Frisaldi et al., 2023; Murray, 2021). Placebo and placebo effect/s definitions have shown discrepancies but have been used for decades (Macedo et al., 2003). These concepts typically suggest that individuals receiving a placebo treatment show improved health outcomes compared to what would have been anticipated if they had not received the placebo (Murray, 2021). The findings of medical placebo research have shown small to large effects on several health conditions (Frisaldi et al., 2023; Tavel, 2014). However, the discussion about placebo and placebo effects remains open (Murray, 2021), and logically, placebo effects could be effective also outside the medical domain (Pollo et al., 2011).

In sports, the placebo effect refers to the improved exercise performance resulting from the belief that one has received a beneficial treatment (Clark et al., 2000; Szabo, 2023). This placebo effect is likely a key factor in all sport and exercise research studies involving human participants (Beedie et al., 2018). In recent decades, there has been a growing interest in this topic, where previous reviews have found a small to moderate improvement in exercise performance (Beedie & Foad, 2009; Chhabra & Szabo, 2024; Hurst et al., 2020), and the findings of sport placebo research are similar to those found in the medical context (Beedie et al., 2018). The placebo effect can potentially enhance athletic performance or performance-related variables and, in some cases, these improvements are comparable in magnitude to those observed using ergogenic aids (Beedie et al., 2018). The potential to achieve this placebo effect in athletic performance has prompted research across various sports, investigating different placebo interventions, such as nutritional, mechanical, or other characteristics, including verbal manipulation (Chhabra & Szabo, 2024; Hurst et al., 2020). However, most of the studies conducted on the placebo effect have been studied from the perspective of ergogenic aids such as carbohydrates (Clark et al., 2000), amino acids (Kalasountas et al., 2007), sodium bicarbonate (McClung & Collins, 2007), or caffeine (Hurst et al., 2019; Valero et al., 2024).

Although a wide range of supplements are promoted for enhancing sports performance, many lack strong evidence supporting their ergogenic effectiveness (Peeling et al., 2018). Only a few (caffeine, creatine, specific buffering agents and nitrate) have good evidence of their benefits (Maughan et al., 2018). In addition, the effectiveness of these ergogenic aids depends on several factors, including the type of athletic event, the specific context in which they are used, the protocol (e.g. timing, dosage) employed and the individual athlete's goals and physiological responsiveness (Burke et al., 2019; Maughan et al., 2018; Peeling et al., 2018). One of the most commonly used ergogenic aids in sports is caffeine (Aguilar-Navarro et al., 2019), due to its well-known beneficial effects on athletic performance (Baltazar-Martins et al., 2020; Grgic et al., 2018; Guest et al., 2021; Salinero et al., 2019). Although caffeine improves several aspects of physical performance, including aerobic and anaerobic activities (Guest et al., 2021), and strength and power exercises (Grgic et al., 2018; Grgic & Varovic, 2022), its use has been more widespread in aerobic sports, perhaps because its benefits in strength/power disciplines were controversial for several years (Giraldez-Costas et al., 2023). However, nowadays there is solid evidence that caffeine is an ergogenic aid for these types of sports (Grgic & Mikulic, 2021; Grgic & Varovic, 2022; Guest et al., 2021). Maybe for this reason, caffeine's use in strength/power-based sports has increased substantially from 2008 to 2015 (Aguilar-Navarro et al., 2019). Thus, caffeine is an ideal substance for studying the placebo effect to maximize the expectations of increased performance, as certain expectations elicit greater placebo responses compared to doubtful expectations (Frisaldi et al., 2023). So, caffeine has become the most commonly used substance to induce a placebo effect in participants (Chhabra & Szabo, 2024; Hurst et al., 2020).

Deceptive caffeine ingestion has been studied in running (Beedie et al., 2007; De La Vega et al., 2017; Hurst et al., 2019; Rohloff et al., 2022; Valero et al., 2024), cycling (Beedie et al., 2006; Duncan, 2010), and resistance performance (Filip-Stachnik et al., 2020; Ortiz-Sánchez et al., 2024) with contradictory results. On cycling performance, Duncan (Duncan, 2010) found a significant placebo effect with deceptive caffeine ingestion on short-term, high-intensity exercise (e.g. Wingate test). In a 10-km time trial, Beedie et al. (Beedie et al., 2006) also found a placebo effect after deceptive caffeine ingestion, and a dose-response relationship emerged, with reduced performance when they believed they had ingested a placebo, 1.3% more power when they believed they had ingested 4.5 mg·kg^{-1} caffeine, and 3.1% more power when they believed they had ingested 9.0 mg·kg^{-1} caffeine. Studies on running endurance performance found improvements with deceptive caffeine ingestion on several times/distances, such as 1000-m running performance (Hurst et al., 2019), 4-km test (Rohloff et al., 2022), and 6-min time trial (Valero et al., 2024). So, belief in caffeine ingestion could propitiate enhanced endurance capacity.

However, controversial results emerged in strength or power performance in resistance exercises. Deceptive caffeine ingestion failed to improve maximal voluntary concentric force (Tallis et al., 2016), or strength variables on bench press or squat exercises (Filip-Stachnik et al., 2020; Ortiz-Sánchez et al., 2024). However, other studies found that placebo intake when the athletes were informed they were taking caffeine, improved the performance of explosive movements (Costa et al., 2019) or repetitions in one set to failure at 60% (Duncan et al., 2009) or 80% repetition maximum (Campelo et al., 2023). Duncan et al. (Duncan et al., 2009) and Campelo et al. (Campelo et al., 2023) found that participants completed more reps (single leg extension and bench press, respectively) when participants perceived they had ingested caffeine, and the RPE was lower in the deceptive caffeine ingestion condition. In contrast, Filip-Stachnik et al. (Filip-Stachnik et al., 2020) found no significant differences in either the number of repetitions completed or one-repetition maximum in the bench press exercise following deceptive caffeine ingestion. Ortiz et al. (Ortiz-Sánchez et al., 2024) observed a significant increase only in two variables of the strength tests (mean velocity bench press at 50% of 1 RM, and rate of force development in squat at 75% of 1RM) but no significant differences were found in the other strength variables studied, where 50%, 75% and 90% 1RM loads were measured both in bench press and squat. So, it is not clear that just the belief of taking caffeine (or other ergogenic aid) would improve sport performance on strength or power performance.

Sprint performance is a key factor for performance in many sports, such as team sports, or sprint events in athletics. Curiously, while some studies have analysed the potential ergogenic effects of caffeine on team sports (Salinero et al., 2019), research about caffeine's effects on sprint events has received minor attention. Specifically in sprint events, Lara et al. (2015) in swimmers and Matsumura et al. (2023) in athletics have demonstrated improvements in sprint performance with acute caffeine ingestion. In the context of the placebo effect, there are controversial results. Beedie et al. (2007) found improved repeated sprint performance, while Hurst et al. (2017) did not find a placebo effect on 5x20 m repeated sprint performance. In athletics, De La Vega et al. (2017) found that drinking an inert liquid, primed with positive information, reduced the time in the 200-m sprint test on recreational runners (≈40 sec for 200-m).

Therefore, it seems that the placebo effect could be incorporated as a simple strategy to improve performance since it does not present any risk to the health of athletes, diminishing the possible side effects of other ergogenic aids used by athletes, such as caffeine, where it has been shown that it can cause nervousness, gastrointestinal discomfort, or insomnia (Pallarés et al., 2013; Salinero et al., 2014). In addition, higher doses of caffeine (i.e., 9 mg/kg of body mass) drastically increased the frequency of the adverse side effects compared with moderate doses (i.e., 3 to 6 mg/kg). For example, with that higher dose, 38% of participants reported gastrointestinal problems, and 54% of subjects reported insomnia or sleep disturbances (Pallarés et al., 2013). However, similar to the placebo effect, it is also possible that the negative effects associated with caffeine consumption may be reproduced in participants who believe they have ingested caffeine. This is the nocebo effect, an undesirable effect resulting from anticipated or conditioned negative outcomes (Beedie et al., 2018). Curiously, the belief in caffeine ingestion was also associated with some minor side effects, such as greater activeness or nervousness (Ortiz-Sánchez et al., 2024; Valero et al., 2024).

Therefore, this study aimed to analyse the placebo effect associated with caffeine on the performance of sprinters in a 60-meter sprint test and a standing triple jump and potential side effects.

MATERIAL AND METHODS

Participants

An a priori sample size estimation revealed that at least 11 participants were required to investigate the potential placebo effect of caffeine with an effect size of 1.15 tested with a two-tailed paired sample t-test ($1 - \beta = 0.9$; $\alpha = .05$). This calculation was based on the effect size obtained with placebo vs. control conditions of the Hurst et al. investigation (2019), and it was performed with G*Power (v3.1.9.7) software. Thirteen trained sprinters (7 men and 6 women) volunteered to complete the experimental procedures (22.77 ± 4.66 years, 64.65 ± 6.52 kg and 173.92 ± 6.47 cm). The participants were classified as Tier 2 (Trained/Developmental) and 3 (Highly trained) (McKay et al., 2022) and presented a punctuation of 884.27 ± 122.29 World Athletics points. They were all sprinters competing in 100, 200 or 400 meters.

Procedures

A repeated, randomized, and counterbalanced experimental design was used to compare the effects of the ingestion of a placebo reported as caffeine (placebo) and a control situation where no substance was ingested (control). Seven participants started with the control condition, and 6 participants started with the placebo condition. Participants were thoroughly informed of potential risks associated with the experimental procedures before providing written informed consent. The study was performed following the principles of the Declaration of Helsinki, and the experimental protocols were approved by the local ethics committee (ref. 28.1.2021CEI-UCJC).

A familiarization session was carried out the week before, even though the athletes were used to this type of testing in their training routines. Secondly, participants were informed about their participation in a "*caffeine effect*" study reinforcing their belief that the intake would be caffeine and not another different substance, as in the case of this study, a placebo substance.

Participants performed the tests twice at the same time of day to avoid circadian influences (Chtourou & Souissi, 2012). In a counterbalanced manner, one group ingested the placebo (100mg of wheat flour in an opaque capsule) on the first day and had no intake on the second day, while the other group did vice versa. To ensure that performance variations could not be attributed to differences in training load between data collections, both measurements were taken one week apart. The evaluation sessions were included within a similar microcycle, specifically scheduled on the day after an easy training session.

Placebo intake was just before starting warm-up, 50 minutes before the tests. Participants were instructed to avoid any ergogenic substance 24 hours before the data collection. In addition, the athletes used the same track spikes on both days (their own competition spikes).

The tests were performed on an athletics track. The warm-up consisted of 15 minutes of jogging followed by mobility and drill exercises. Then, five 50-meter repetitions were carried out increasing speed throughout each repetition. Recovery time was 1 minute.

First, the standing triple jump test was carried out. Participants were instructed to start from feet together, and then participants performed 3 jumps altering the landing leg and ending in the long jump pit on the last jump. Each participant performed two attempts. The longest jump was used as the test score. Before 5 min of recovery, participants performed a 60-meter sprint test with a standing start (without starting blocks). Double photocells (Witty-Gate, Microgate, Italy) were employed to measure time. This system ensures that the photocells are interrupted by the chest and not by the athlete's leading arm. The lower photocells were mounted around the level of the hips, and the upper photocells were mounted 0.20 m higher, as recommended by previous studies (Yeadon et al., 1999) and throughout the 60 m. Therefore, we obtained split times from start to the 10-meter line; from 10 to the 30-meter line; from start to the 30-meter line; from 30 to 60-meter line, and 60-meter total time.

Finally, the morning after carrying out the test, participants in the placebo condition completed a questionnaire assessing caffeine-related side effects. They were provided with a link to an electronic form (Google Forms) to report any potential side effects. The form utilized a dichotomous (yes/no) scale to indicate the presence or absence of specific symptoms, including nervousness, digestive disturbances, or sleep difficulties. This questionnaire had been previously used to evaluate side effects associated with caffeine consumption (Salinero et al., 2014).

Analysis

Data is presented as mean ± SD. Normality was checked using Shapiro-Wilk test. The variables followed a normal distribution enabling the use of parametric statistics. A paired samples student's t-test was performed to analyse differences between both conditions. In addition, Cohen's *d* was carried out to check the effect size (<0.20 trivial, ≥0.20-0.59 small, ≥0.60-1.19 moderate, ≥1.20-1.99 large, and ≥2.00 very large) (Hopkins, 2016). The significance level was established at $p < .05$. The JASP 0.18.3 software was employed to execute all calculations.

RESULTS

Table 1 illustrates the split times and complete time of the 60-meter sprint test and the distance covered in the standing triple jump in the placebo and control conditions. No significant differences were found in any parameter analysed with trivial (0 – 10 meters, 30 – 60 meters, and triple jump) or small (10 – 30 meters, 0 – 30 meters, and 0 – 60 meters) effect sizes for all parameters.

Table 1. Split and complete time on 60-m sprint test and distance covered in the standing triple jump.

	Placebo	**Control**	***p***	**d**
0 – 10 m	1. 74 ± 0.12	1.74 ± 0.09	.77	0.08
10 – 30 m	2.41 ± 0.14	2.42 ± 0.14	.43	0.23
0 – 30 m	4.15 ± 0.24	4.16 ± 0.22	.46	0.21
30 – 60 m	3.38 ± 0.23	3.39 ± 0.22	.67	0.12
0 – 60 m	7.52 ± 0.46	7.55 ± 0.43	.49	0.20
Triple jump	7.28 ± 0.84	7.28 ± 0.87	.95	0.02

Figure 1 depicts the individual analysis of 60-meter total times and the standing triple jump. Figure 1A shows that only 5 out of 13 improved the 60-meter sprint test, while Figure 1B points out how 7 out of 13 athletes improved the standing triple jump performance.

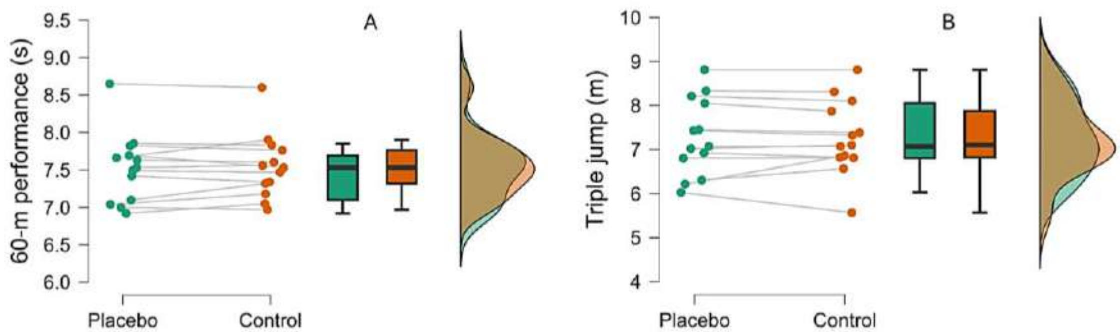

Figure 1. Individual 60 meters total times (Figure 1A) and individual standing triple jump (Figure 1B).

Finally, the self-reported side effects are outlined in Table 2. The main side effects reported the day that athletes ingested the placebo capsule were activeness (53.8%), nervousness (23.1%), and insomnia (15.4%).

Table 2. Self-reported side-effects the day that athletes ingested the placebo.

	% of affirmative responses
Nervousness	23.1
Gastrointestinal problems	0
Activeness	53.8
Irritable	0
Muscular pain	7.7
Headache	7.7
Increased urine production	7.7
Insomnia	15.4

DISCUSSION

The aim of the study was to analyse the potential placebo effect derived from deceptive caffeine ingestion on the performance of sprinters in a 60-meter sprint test and a standing triple jump. To address this objective, 13 trained athletes completed a 60-meter sprint test and a triple jump on two occasions: after ingesting a placebo informed as caffeine and without ingesting any substance (control) in a randomized and counterbalanced design. The results revealed that the belief of having consumed caffeine did not improve sprint performance or increase jumping ability, despite participants reporting feeling more active on the day they took the placebo. Therefore, it seems that the placebo effect does not appear to be an effective strategy for enhancing performance in this type of test.

Previous studies have found performance improvements following the ingestion of supposed caffeine in longer-distance running tests, such as 1000 meters (Hurst et al., 2019) or a 6-minute running test (Valero et al., 2024), while other studies focusing on strength-power tests have not found a significant placebo effect (Filip-Stachnik et al., 2020; Ortiz-Sánchez et al., 2024). Thus, it seems that the placebo effect may be more evident in longer-duration tests where volitional aspects may have a greater impact on performance. In contrast, the placebo effect did not enhance performance in shorter tests where neuromuscular components predominate. In endurance running tests, what was reported as a placebo effect could be mediated by the result of the participants having adopted a less conservative and more optimal pacing strategy (Beedie et al., 2018). Hurst et al. (2019) observed a faster pace during the first half of their 1000-meter trials, which resulted in improved overall performance. This suggests that deceptive caffeine intake may influence participants' perception of their speed capabilities (Hurst et al., 2019). However, in sprint events like the 60-meter sprint, which are short all-out tests, there is no strategic distribution of energy. This may be one reason why the placebo effect did not influence these athletes. However, further studies are needed to confirm these findings.

The deceptive caffeine ingestion led 7 out of 13 athletes to perceive themselves as more active. However, as we have observed, this did not result in improved performance. Notably, 23% of the athletes reported feeling more nervous, which could negatively impact performance in competition. These findings align with previous research (Ortiz-Sánchez et al., 2024; Valero et al., 2024). Ortiz-Sánchez et al. (2024) reported that 33% of participants experienced nervousness, while Valero et al. (2024) observed this effect in 7.7% of participants. Therefore, individual responses to deceptive caffeine ingestion should be considered before recommending the use of caffeine-related placebos in competition. In future studies, it would be interesting to explore whether the perception of side effects is linked to the typical side effects associated with the reported substance. In such cases, it may be advisable to suggest the use of other substances without known side effects to the participants.

This experimental study presents some limitations that should be discussed. In the 60-meter test, only one repetition was performed, which means day-by-day individual variability may have influenced the outcomes. Due to the nature of the test and the fact that the participants were trained sprinters, it would be impossible to perform a second attempt within a short time frame under the same (non-fatigued) conditions (Tomazin et al., 2012). However, this approach provides a more ecological experimental design, as athletes only have a single attempt during their competitions. Additionally, athletes with positive expectations about a treatment would experience a greater improvement in performance compared to those with no expectations (Beedie et al., 2018). To minimize this limitation, athletes were informed about the ergogenic effects of caffeine and were convinced that the dose administered was optimal for enhancing performance in these tests.

CONCLUSIONS

Deceptive caffeine ingestion did not alter performance in sprint and triple jump performance in trained athletes, while some minor side effects appeared. Individual responses to placebo ingestion should be carefully considered before making recommendations for sprint athletes.

AUTHOR CONTRIBUTIONS

All authors contributed significantly to the final version of this manuscript and to the interpretation of the results. Study design: PM, VM, FGM and JJS. Data collection: AA, VM, FV, PM, and JJS. Statistical analysis: FGM and JJS. Data interpretation: FV, FGM and JJS. Literature search: PM, FV and JJS. Writing-original draft preparation: AA, FV, FGM and JJS. Writing- review and editing: All authors. Supervision: FGM and JJS. Project administration: JJS. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

The authors declare no conflict of interest. The experiments comply with the current laws of the country in which they were performed.

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ORIGINAL ARTICLE

Evolution of technical-tactical performance indicators based on the year of college of the male goalkeepers of the NCAA Division I of the United States

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ABSTRACT

The objective of the study was to analyse the evolution of game statistics as a function of the year of college of NCAA Division I male goalkeepers. The sample was all 43,079 goalkeeper's participations (average of 3916 goalkeeper's participations of 405 goalkeepers per season) from 202 male teams from Division I of the National Collegiate Athletic Association (NCAA) of United States (2010-2021 seasons). A retrospective non-experimental design was used. The variables studied were goalie games played, percentage of goalie games started, goals allowed, goalkeeper's goals-against average, saves, saves percentage, shutouts, combined shutouts, yellow cards, and red cards. A one-way ANOVA was used to study the evolution between goalkeepers from top and bottom teams. To analyse the differences according to top and bottom teams, a T-test and a discriminant analysis were performed. As goalkeepers gain experience, their participation in games played and games started increases significantly (second, third- and fourth-year goalkeepers) and their effectiveness increases (decrease in goals allowed and increase in shutouts). These findings highlight the importance of experience, training, maturity in goalkeeper performance and the differences in recruitment between teams.
Keywords: Performance analysis, Team sports, Football, Athletic performance, Motor skills, Goalkeeper.

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INTRODUCTION

In football, the goalkeeper is responsible for protecting the goal, coordinating the defence, and initiating the attack phase (Shamardin & Khorkavyy, 2015). The goalkeeper's performance is influenced by multiple aspects, such as technical, tactical, psychological, sociological, or physical factors (Otte et al., 2022). The development process of a goalkeeper is long. Most performance goalkeepers reach their peak performance later than field players (Jamil & Kerruish, 2020). During their development process, goalkeepers improve their performance thanks to their maturation, accumulation of experiences, and the increase in specialized training (Otte et al., 2020). The study of the evolution of players throughout their training process has focused mainly on field players and absolute performance categories (Sarmento et al., 2018). There are a small number of studies that analyse the evolution of the goalkeeper and his transition through the different stages of his training (Tienza-Valverde et al., 2023). The transition from the development stage to the performance stage (U-18 to U-23) is a particularly critical stage in this process. Knowing how goalkeepers develop and obtaining benchmarks for their development can help to better understand their development process and guide their development and training at this stage.

Most published research on soccer goalkeepers has prioritized the study of physical and physiological aspects. These aspects are influenced by the team's playing style and their participation in the game (Otte et al., 2020; White et al., 2018). Most of the studies on technical-tactical performance indicators in soccer goalkeepers have focused on the goalkeeper's contribution in defensive actions during the game, in set pieces, or in penalty kicks (e.g., Furley et al., 2017; Sainz De Baranda et al., 2008; Tienza-Valverde et al., 2023). In offensive terms, different works have analysed the role of the soccer goalkeeper in initiating the construction of the team's offensive play, and maintaining possession of the ball (e.g., Casal et al., 2023; Mikikis et al., 2021).

Technical-tactical actions have also been analysed based on contextual aspects, such as playing at home or away (Liu et al., 2015) or based on the level of the teams (Sainz de Baranda et al., 2019). These works show how the level of the teams influences the performance of the goalkeeper. Goalkeepers from higher-level teams make fewer saves, touches of the ball, passes, interceptions, and clearances compared to goalkeepers from lower-level teams (Sainz de Baranda et al., 2019). In the review carried out, works have been found that analyse the evolution in this age group (U23) in field players. Players from higher level teams show greater development, participation in matches and shots on goal, compared to players from lower-level teams (Caicedo-Parada et al., 2024). In the review carried out, no information was found on the development process of U23 goalkeepers at a technical-tactical level.

This paper analyses the development of goalkeepers aged 18 to 22 years and seeks to provide reference values for this stage of their training process. The study analyses the four-year period of American goalkeepers playing in the NCAA Division I. The training model through school and university teams used in the United States differs from the performance academies paradigm used in other countries. However, their analysis can provide information on the evolution of goalkeepers in the U23 category.

The hypothesis of the present study was that participation in the game and the effectiveness of the actions of goalkeepers in the U23 categories increases with increasing age, years of training, and experience. The objective of the study was to analyse the evolution of game statistics as a function of the year of college of NCAA Division I male goalkeepers.

METHOD

Sample

The sample was all 43.079 goalkeeper's participations (average of 3916 goalkeeper's participations of 405 goalkeepers per season) from 202 male teams from Division I of the National Collegiate Athletic Association (NCAA) of United States. The sample was from season 2010-2011 through 2020-2021 seasons. Goalkeepers were classified according to their year in college: a) 1st year or freshman, b) 2nd year or sophomore, c) 3rd year or junior, and d) 4th year or senior. Goalkeeper's data were obtained from the publicly accessible statistics website of the official NCAA website (https://stats.ncaa.org/).

Design

A retrospective non-experimental design was used. The variables studied were goalie games played, percentage of goalie games started, goals allowed, goalkeeper's goals-against average (GAA = (Goals allowed x 90) ÷ minutes played), saves, saves percentage, shutouts, combined shutouts, yellow cards, and red cards. The unit of analysis was the season. The variables were recorded in absolute values per season and recalculated in relative values for the total number of matches played for each player (absolute value of the variable, divided by the number of matches played by the player in the season). Players were classified into top and bottom based on the team's winning coefficient in each season (win was giving a score of 1, a tie was given a score of .5, and a loss was scored as 0). Top teams had a winning coefficient above 0.500 and bottom teams had a winning coefficient below 0.500.

Data of the variables obtained were collected for the summation of the match reports of each team in each season. To establish the reliability of the match report, a researcher observed five matches from different seasons. The observer had a master's degree in Sport Science and more than five years of experience with sports analytics in football. The observation was done using the software Lince Plus (Soto-Fernández et al., 2022). The rater reliability was calculated using Cohen's Kappa for the categorical variables and an Interclass Correlation Coefficient (ICC) for the continuous variables. All the variables studied had a value of 1.

Procedure and statistical analysis

A one-way ANOVA was used to study the evolution between goalkeepers from top and bottom teams. To analyse the differences according to top and bottom teams, a T-test and a discriminant analysis were performed. Structural coefficients (SC) were used to discriminate top and bottom teams (SC above 0.30) (Tabachnick & Fidell, 2013). Significance level was set at $p < .05$. The effect size was established with the eta square. The following scale was used to assess Effect Size: N = No effect (<0.20) S = Small (0.20 - 0.49) M = Medium (0.50 - 0.79) L = Large (0.80 - 1.19) XL = Extra Large (>1.2) (Sawilowsky, 2009). All analyses were conducted using the Statistical Package for the Social Sciences (SPSS, version 28.0.0.0., IBM, Boston, IL, USA). Tables with the absolute values of the variables studied can be found in Tables 4, 5 and 6.

RESULTS

In the analysis of the evolution of the goalkeepers both at a general level and differentiating between the top and bottom teams (Table 1 and 2), it is observed that the more experience and training the goalkeepers have, the more their values increase in the variables "*goalie games played*" and "*goalie games started*". The variable saves percentage increases from the 2nd to the 3rd year. The variables goals allowed, goalkeeper's goals-against average, saves, combined shutouts, yellow cards, and red cards changed between the different years in top and bottom teams. The variable saves percentage shows an increase over the years of

Table 1. Evolution of the relative values of participation and game statistics as a function of the player's year in top level college men's football goalkeepers (Division I - NCAA, U.S. [season 2010 to 2021]).

Variables	1st year (Freshman)		2nd year (Sophomore)		3rd year (Junior)		4th year (Senior)	
	M	SD	M	SD	M	SD	M	SD
Goalie GP	0.544[bcd]	0.439	0.644[acd]	0.493	0.744[abd]	0.499	0.813[abc]	0.507
Goalie GS (%)	72.2[cd]	36.7	75.5[cd]	36.3	80.8[ab]	33.3	82.0[ab]	32.8
G. allowed	1.73	2.35	1.76	2.99	1.66	2.31	1.65	2.45
GAA	1.55	1.34	1.54	1.83	1.42	1.23	1.42	1.93
Saves	4.14	5.94	4.3	6.97	4.26	5.37	4.34	6.04
SV_Pct	0.659	0.229	0.657[c]	0.237	0.685[b]	0.208	0.68	0.221
Shutouts	0.236	0.493	0.276	0.603	0.295	0.594	0.301	0.589
Comb_sho	0.02	0.156	0.015	0.148	0.019	0.173	0.02	0.172
Yellow cards	0.016	0.075	0.02	0.062	0.022	0.064	0.022	0.055
Red cards	0.002	0.024	0.004	0.051	0.002	0.019	0.002	0.017

Note. *Statistical differences were analysed using an ANOVA test; a Significantly different from 1st year (Freshman); b Significantly different from 2nd year (Sophomore); c Significantly different from 3rd year (Junior); d Significantly different from 4th year (Senior). Goalie GP: Goalie Games Played, Goalie GS (%): Percentage Goalie Games Started, G. Allowed: Goals Allowed, GAA: Goalkeeper's goals-against average, SV_Pct: Saves Percentage, Comb_Sho: Combined Shutouts.*

Table 2. Evolution of the relative values of participation and game statistics as a function of the player's year in bottom level college men's football goalkeepers (Division I - NCAA, U.S. [season 2010 to 2021]).

Variables	1st year (Freshman)				2nd year (Sophomore)				3rd year (Junior)				4th year (Senior)			
	Top 50		Bottom 50		Top 50		Bottom 50		Top 50		Bottom 50		Top 50		Bottom 50	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Goalie GP	0.563[bcd]	0.486	0.528[bcd]	0.395	0.664[acd]	0.538	0.623[ad]	0.441	0.820[ab]	0.539	0.659[ad]	0.436	0.873[ab]	0.537	0.740[abc]	0.458
Goalie GS (%)	70.1[cd]	39.2	73.9[cd]	34.5	72.6[cd]	39	78.5	33	80.3[ab]	35.4	81.4[a]	30.9	80.7[ab]	35	83.7[a]	29.7
G. allowed	1.23	1.59	2.13	2.75	1.3	2.09	2.25	3.65	1.28	1.79	2.08	2.72	1.32	1.72	2.05	3.06
GAA	1.19	1.2	1.85	1.39	1.2	1.64	1.9	1.95	1.09	1.19	1.78	1.17	1.22	2.35	1.68	1.18
Saves	3.38	5.36	4.75	6.32	3.67	5.61	4.96	8.12	3.9	5.26	4.67	5.46	3.87	4.97	4.92	7.09
SV_Pct	0.666	0.258	0.653	0.202	.660[c]	0.271	0.655	0.196	0.705[b]	0.229	0.662	0.179	0.684	0.241	0.674	0.193
Shutouts	0.301	0.608	0.185	0.368	0.351	0.755	0.196	0.366	0.377	0.696	0.203	0.436	0.382	0.696	0.202	0.402
Comb_sho	0.031	0.207	0.01	0.095	0.024	0.194	0.006	0.071	0.028	0.221	0.01	0.091	0.028	0.213	0.01	0.102
Yellow cards	0.017	0.081	0.016	0.07	0.021	0.071	0.019	0.051	0.019	0.053	0.025	0.074	0.02	0.046	0.024	0.064
Red cards	0	0.008	0.004	0.032	0.005	0.058	0.002	0.042	0.002	0.015	0.004	0.022	0.001	0.011	0.004	0.021

Note. Statistical differences were analysed using an ANOVA test; a Significantly different from 1st year (Freshman); b Significantly different from 2nd year (Sophomore); c Significantly different from 3rd year (Junior); d Significantly different from 4th year (Senior). Goalie GP: Goalie Games Played, Goalie GS (%): Percentage Goalie Games Started, G. Allowed: Goals Allowed, GAA: Goalkeeper's goals-against average, SV_Pct: Saves Percentage, Comb_Sho: Combined Shutouts.

Table 3. Differences as a function of team level in relative participation values and game statistics as a function of player year in college in men's football goalkeepers (Division I - NCAA, U.S. [season 2010 to 2021]).

Variables	**1st year (Freshman)**				**2nd year (Sophomore)**				**3rd year (Junior)**				**4th year (Senior)**			
	Top 50 - Bottom 50				Top 50 - Bottom 50				Top 50 - Bottom 50				Top 50 - Bottom 50			
	Differ	%	Sig.	ES	Differ	%	Sig.	ES	Differ	%	Sig.	ES	Differ	%	Sig.	ES
Game played	0.035	6.21	.228	**0.438^{S}**	0.041	6.17	.156	**0.493^{S}**	0.161	19.6	**<.001**	**0.493^{S}**	0.133	15.2	**<.001**	**0.503^{M}**
Game started (%)	-3.8	-5.42	.113	36.7	-5.9	-8.12	**.005**	**36.2^{XL}**	-1.1	-1.36	.559	33.3	-3	-3.71	.133	32.8
Goals allowed	-0.9	-73.1	**<.001**	**2.30^{XL}**	-0.95	-73	**<.001**	**2.96^{XL}**	-0.8	-62.5	**<.001**	**2.28^{XL}**	-0.73	-55.3	**<.001**	**2.42^{XL}**
GAA	-0.01	-0.84	**<.001**	1.3	-0.7	-58.3	**<.001**	1.8	-0.69	-63.3	**<.001**	1.18	-0.46	-37.7	.568	1.91
Saves	-1.37	-40.5	**<.001**	**5.91^{XL}**	-1.29	-35.1	**.002**	**6.95^{XL}**	-0.77	-19.7	**.017**	**5.36^{XL}**	-1.05	-27.1	**.005**	**6.02^{XL}**
SV_Pct	0.013	1.95	.414	0.229	0.005	0.75	.697	0.237	0.043	6.09	**<.001**	**0.207^{S}**	0.01	1.46	.438	0.221
Shutouts	0.116	38.5	**<.001**	**0.490^{S}**	0.155	44.1	**<.001**	**0.599^{M}**	0.174	46.1	**<.001**	**0.587^{M}**	0.18	47.1	**<.001**	**0.582^{M}**
Comb_sho	0.021	67.7	.057	0.155	0.018	75	.052	0.147	0.18	642.8	.078	0.173	0.018	64.2	.094	0.172
Yellow cards	0.001	5.88	.966	0.075	0.002	9.52	.705	0.062	-0.006	-31.5	.077	0.064	-0.004	-20	.228	0.055
Red cards	-0.004	0	**.02**	**0.024^{S}**	0.003	60	.409	0.051	-0.002	-100	.08	0.019	-0.003	-300	**.01**	**0.017^{N}**

Note. Statistical differences were analysed using an Independent T-test. TE = Effect Size: N = No effect (<0.20) S = Small (0.20 - 0.49) M = Medium (0.50 - 0.79) L = Large (0.80 - 1.19) XL = Extra Large (>1.2). Goalie GP: Goalie Games Played, Goalie GS (%): Percentage Goalie Games Started, GAA: Goalkeeper's goals-against average, SV_Pct: Saves Percentage, Comb_Sho: Combined Shutouts.

Table 4. Evolution of the absolute values of participation and game statistics as a function of the player's year in top level college men's football goalkeepers (Division I - NCAA, U.S. [season 2010 to 2021].

Variables	**1st year (Freshman)**		**2nd year (Sophomore)**		**3rd year (Junior)**		**4th year (Senior)**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Goalie GP	7.62^{bcd}	6.14	9.02^{acd}	6.9	10.4^{abd}	6.99	11.3^{abc}	7.1
Goalie GS	6.75^{bcd}	6.43	8.28^{acd}	7.23	9.75^{abd}	7.38	10.7^{abc}	7.52
G. allowed	10.1^{bcd}	9.52	11.5^{acd}	10.1	12.6^{abd}	9.59	13.7^{abc}	10.1
GAA	1.55	1.34	1.54	1.83	1.42	1.23	1.42	1.93
Saves	26.2^{bcd}	25.8	31.3^{acd}	28.3	36.4^{abd}	29	40.6^{abc}	30.7
SV_Pct	0.659	0.229	0.657^{c}	0.237	0.685^{b}	0.208	0.68	0.221
Shutouts	1.68^{bcd}	2.35	2.20^{acd}	2.72	2.73^{abd}	3.02	3.10^{abc}	3.16
Comb_sho	0.06	0.358	0.05	0.313	0.05	0.307	0.05	0.282
Yellow cards	0.16^{bcd}	0.492	0.23^{a}	0.52	0.26^{a}	0.582	0.29^{a}	0.597
Red cards	0.03	0.163	0.02	0.162	0.03	0.179	0.04	0.198

Note. Statistical differences were analysed using an ANOVA test; a Significantly different from 1st year (Freshman); b Significantly different from 2nd year (Sophomore); c Significantly different from 3rd year (Junior); d Significantly different from 4th year (Senior). Goalie GP: Goalie Games Played, Goalie GS: Goalie Games Started, G. Allowed: Goals Allowed, GAA: Goalkeeper's goals-against average, SV_Pct: Saves Percentage, Comb_Sho: Combined Shutouts.

Table 5. Evolution of the absolute values of participation and game statistics as a function of the player's year in bottom level college men's football goalkeepers (Division I - NCAA, U.S. [season 2010 to 2021]).

Variables	**1st year (Freshman)**				**2nd year (Sophomore)**				**3rd year (Junior)**				**4th year (Senior)**			
	Top 50		Bottom 50		Top 50		Bottom 50		Top 50		Bottom 50		Top 50		Bottom 50	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Goalie GP	7.89[bcd]	6.81	7.40[bcd]	5.53	9.30[acd]	7.53	8.73[ad]	6.18	11.4[ab]	7.55	9.24[ad]	6.1	12.2[ab]	7.52	10.3[abc]	6.41
Goalie GS	7.07[bcd]	7.15	6.48[bcd]	5.76	8.60[acd]	7.92	7.95[ad]	6.43	10.8[ab]	8.01	8.52[ad]	6.38	11.5[ab]	7.99	9.78[abc]	6.77
G. allowed	8.12[cd]	7.93	11.7[bcd]	10.3	9.53[cd]	8.77	13.5[ad]	11	11.4[ab]	8.6	13.9[ad]	10.4	12.1[ab]	8.61	15.8[abc]	11.4
GAA	1.62	8.84	1.85	1.39	1.2	1.64	1.9	1.95	1.09	1.19	1.78	1.17	4.18	72.9	2.28	13.4
Saves	24.1[bcd]	25.7	27.9[bcd]	25.9	29.4[acd]	27.9	33.3[ad]	28.5	37.6[ab]	29.2	35.2[ad]	28.9	40.1[ab]	30.4	41.2[abc]	31
SV_Pct	0.666	0.258	0.653	0.202	0.660[c]	0.271	0.655	0.196	0.705[b]	0.229	0.662	0.179	0.684	0.241	0.674	0.193
Shutouts	2.35[cd]	2.98	1.12[bcd]	1.45	2.90[cd]	3.23	1.45[ad]	1.78	3.75[ab]	3.46	1.60[a]	1.89	4.13[ab]	3.54	1.83[ab]	2.01
Comb_sho	0.1	0.486	0.03	0.191	0.07	0.405	0.02	0.164	0.08	0.401	0.02	0.133	0.07	0.358	0.02	0.134
Yellow cards	0.15[cd]	0.45	0.16[cd]	0.525	0.24	0.53	0.21	0.509	0.26[a]	0.588	0.26[a]	0.576	0.30[a]	0.614	0.28[a]	0.575
Red cards	0.01	0.109	0.04	0.196	0.03	0.191	0.02[d]	0.123	0.2	0.154	0.04	0.203	0.03	0.165	0.05[b]	0.232

Note. Statistical differences were analysed using an ANOVA test; a Significantly different from 1st year (Freshman); b Significantly different from 2nd year (Sophomore); c Significantly different from 3rd year (Junior); d Significantly different from 4th year (Senior). Goalie GP: Goalie Games Played, Goalie GS: Goalie Games Started, G. Allowed: Goals Allowed, GAA: Goalkeeper's goals-against average, SV_Pct: Saves Percentage, Comb_Sho: Combined Shutouts.

Table 6. Differences as a function of team level in absolute participation values and game statistics as a function of player year in college in men's football goalkeepers (Division I - NCAA, U.S. [season 2010 to 2021]).

Variables	**1st year (Freshman)**				**2nd year (Sophomore)**				**3rd year (Junior)**				**4th year (Senior)**			
	Top 50 - Bottom 50				Top 50 - Bottom 50				Top 50 - Bottom 50				Top 50 - Bottom 50			
	Differ	%	Sig.	ES	Differ	%	Sig.	ES	Differ	%	Sig.	ES	Differ	%	Sig.	ES
G. G. played	0.49	6.21	.228	6.14	0.57	6.12	.156	6.9	2.16	18.9	**<.001**	6.9	1.9	15.5	**<.001**	7.04
G. G. started	0.59	8.34	.162	6.43	0.65	7.55	.12	7.23	2.28	21.1	**<.001**	7.29	1.72	14.9	**<.001**	7.47
G. allowed	-3.58	-44	**<.001**	9.35	-3.97	-41.6	**<.001**	9.95	-2.5	-21.9	**<.001**	9.51	-3.7	-30.5	**<.001**	10
GAA	-0.01	-0.84	**<.001**	1.3	-0.7	-58.3	**<.001**	1.8	-0.69	-63.3	**<.001**	1.18	-0.46	-37.7	.568	1.91
Saves	-3.8	-15.7	**.029**	25.8	-3.9	-13.2	**.017**	28.2	2.4	6.38	.166	29	-1.1	-2.74	.578	30.7
SV_Pct	0.013	1.95	.414	0.229	0.005	0.75	.697	0.237	0.043	6.09	**<.001**	0.207	0.01	1.46	.438	0.221
Shutouts	1.23	52.3	**<.001**	2.27	1.45	50	**<.001**	2.63	2.15	57.3	**<.001**	2.82	2.3	55.6	**<.001**	2.95
Comb_sho	0.07	70	**.008**	0.356	0.05	71.4	**.008**	0.312	0.06	75	**<.001**	0.305	0.05	71.4	**.001**	0.28
Yellow cards	-0.01	-6.66	.929	0.493	0.03	12.5	.333	0.52	0	0	.889	0.582	0.02	6.66	.633	0.597
Red cards	-0.03	-300	**.028**	0.163	0.01	33.3	.096	0.162	-0.02	-10	.072	0.179	-0.02	-66.6	**.041**	0.198

Note. Statistical differences were analysed using an Independent T-test. TE = Effect Size: N = No effect (<0.20) S = Small (0.20 - 0.49) M = Medium (0.50 - 0.79) L = Large (0.80 - 1.19) XL = Extra Large (>1.2). Goalie GP: Goalie Games Played, Goalie GS (%): Percentage Goalie Games Started, GAA: Goalkeeper's goals-against average, SV_Pct: Saves Percentage, Comb_Sho: Combined Shutouts.

experience in both top and bottom teams. The variables saves and goalkeeper's goals-against average were higher in the last year of university goalkeepers at university.

Regarding the differences between the top and bottom teams (Table 3), the top teams have a significantly higher number of goals allowed, saves and scoreless games than the teams with a lower competitive level in all the analysed years of experience as a university goalkeeper. The effect sizes for change across years in college were small for the variables saves percentage (3rd year) and red cards (1st year), medium for the variables game played (4th year), shutouts (2nd, 3rd, 4th year), and extra-large for the variables game started (2nd year), goals allowed and saves across years.

DISCUSSION AND CONCLUSIONS

The aim of this study was to analyse the evolution of game statistics based on the year of college of male goalkeepers in the NCAA Division I in the United States. The results confirm the working hypothesis and show an increase in the number of games played and games played as a starter for second-, third- and fourth-year goalkeepers, respectively. As goalkeepers increase in age, experience, and years of training, there is an increase in game participation, save frequency, and save percentage. The increase in saves and shutouts shows the evolution thanks to training and the increase in their experience. These improvements lead to a higher level of skill of the goalkeepers which reduces the goals allowed throughout their training process. These results show that goalkeepers evolve throughout the training process. This improvement means that the technical-tactical objectives in training and competition must be adjusted.

The defensive indicators related to infringements show a progressive increase in yellow cards over the four years. One of the possible causes could be an increase in the level of intensity and competitiveness of goalkeepers as their experience increases or when they are in their final year. Goalkeepers who are in a defensive position within the goal area are exposed to risky situations and receive warnings, especially if they increase the intensity and competitiveness of their actions (Ruiz-Solano et al., 2022). These results are consistent with previous studies in this age group, evolution of NCAA Division I male field players (Caicedo-Parada et al., 2024). With increasing age, training, and accumulated experience, there is an improvement in game participation and an increase in the intensity of their actions (e.g., infractions, such as yellow and red cards).

When analysing the ranking of teams according to their win coefficient, goalkeepers from higher-level teams show better values. Freshman goalkeepers from higher-level teams show fewer red cards (small effect size). Sophomore goalkeepers from higher level teams have a higher number in game started (extra-long effect size). Sophomore, junior, and senior goalkeepers on higher-level teams perform a greater number of shutouts (small effect size). Senior goalkeepers from higher level teams have fewer goals allowed and more saves, and game played (medium effect size, except game played with small effect size). These results show that goalkeepers from the teams with the best ranking significantly increased their participation and showed greater effectiveness in their actions. This may be because goalkeepers on higher ranked teams have better training and preparation in more demanding environments with better resources. This helps them improve their skills and techniques. Other possible causes include higher-ranked teams drafting goalies with more potential for improvement, better sequencing goalie rotations on their rosters, or employing goalie analysis and evaluation strategies to help goalies improve. These causes may be behind the differences in the evolution of goalkeepers between teams with better and worse rankings in various variables throughout their years of experience.

The goalkeeper's development cycle, from his integration into the team to his consolidation as a starter, depends on participation, competitive experience, and adaptation to the game. Goalkeepers in higher-ranked teams progress more due to the technical and competitive demands of the environment. Accumulated experience and exposure to a higher competitive level facilitate these improvements. In the case of senior year goalkeepers, compared to first year goalkeepers, a medium improvement is observed in the variable of games without conceding goals, which indicates a continuous evolution and a refinement of skills over time. This could be because senior goalkeepers have accumulated more playing time, allowing them to better anticipate plays and make more effective decisions (Clemente et al., 2020). These differences respond to individual factors, training level, and team dynamics that influence the evolution of goalkeepers according to their team's ranking. These results are consistent with previous studies indicating that goalkeepers from higher-ranked teams make fewer saves compared to those from lower-ranked teams (Liu et al., 2015; Sainz De Baranda et al., 2008). On the other hand, in first-year goalkeepers a small effect size is evident, compared to goalkeepers from older years, with no significant effect on variables such as red cards. This could be due to a lack of experience in high-pressure situations at this level of competition. Less experienced goalkeepers tend to be more cautious and less likely to engage in risky plays that result in fouls. The findings highlight the need to set specific goals based on the level of competition and the academic year at the university. These values can serve as reference points and should be supplemented with statistics from previous seasons of the team and goalkeeper in each conference and level of competition. This will allow you to evaluate progress and adjust motivational and training strategies effectively.

Analysis of the evolution of game statistics in NCAA Division I men's goalkeepers reveals that as goalkeepers gain experience, their participation in games played and games as starters (second, third- and fourth-year goalkeepers) significantly increases. For higher-ranked teams, the decrease in goals allowed and the increase in shutouts indicate an improvement in defensive capabilities and strategic decision-making. In contrast, lower-ranked teams have a higher number of cards and goals allowed, evidencing limitations in technical training and less efficient tactics over the years. These findings highlight the importance of experience, training, maturity in goalkeeper performance and the differences in recruitment between teams. As college goalkeepers progress through their college careers, there is an increase in the number of fouls and yellow cards received, possibly due to a greater assumption of responsibility and the competitive pressure faced. Maturity and the development of psychological skills also play a crucial role in their overall performance and in managing high-pressure situations (Matthews et al., 2021).

This study provides information on the evolution of goalkeepers and establishes reference values according to their year and the level of their team. However, it has certain limitations by focusing only on general game variables. This work does not analyse individual actions with or without the ball, physical aspects or specific team playing styles. For a deeper understanding of goalkeeper development in the transition stage from U18 to senior category, future research is needed that addresses physical, tactical, and cognitive aspects. This would allow for a more detailed analysis and deeper understanding of the factors that influence the development of college goalkeepers.

AUTHOR CONTRIBUTIONS

The concept for this study was developed by the second and third authors (Enrique Ortega and José M. Palao), and the experiment was designed by the first and third authors (Sergio Caicedo and José M. Palao). Data acquisition and reduction for the analysis were performed by the first author (Sergio Caicedo). All three authors participated in the data analysis and contributed to the writing of the article for this publication.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

The impact of a 6-week strength training program on physiological and hematological metrics in elite Ethiopian middle- to long-distance runners

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ABSTRACT

This study examined the effects of a 6-week strength training (StT) program on elite middle- to long-distance runners (1,500m–10,000m). While strength training is recognized for improving athletic performance, its specific impact on physiological and haematological parameters in Ethiopia remains unclear. Twenty-one elite athletes underwent pre- and post-training assessments, measuring resting heart rate (RHR), maximal oxygen consumption (VO_{2max}), 5000m race time, 400m speed, and haematological markers, including red blood cell (RBC) count, white blood cell (WBC) count, haemoglobin (Hb), and haematocrit (Hct). Results showed that 5000m performance significantly improved ($p < .001$), demonstrating the positive effect of StT on endurance. Regression and ANOVA analyses revealed strong predictive relationships for VO_{2max} ($R^2 = 0.304$, $p = .010$), 5000m time ($R^2 = 0.719$, $p < .001$), 400m speed ($R^2 = 0.784$, $p < .001$), and Hct levels ($R^2 = 0.894$, $p < .001$). No significant changes were found in RBC, WBC, or Hb levels. These findings suggest strength training enhances endurance performance without significantly affecting haematological parameters, emphasizing the need for further research on long-term haematological adaptations. This research contributes valuable insights into the effectiveness of strength training interventions for enhancing athletic performance.

Keywords: Performance analysis, Exercise therapy, Strength training, Haematologic tests, Sport performance, Physiological processes, Endurance running.

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INTRODUCTION

Strength training (StT) has long been debated as a tool for improving endurance performance, particularly in middle- and long-distance athletes (MLDA) (Tomschi, Bloch, & Grau, 2018). Recent studies suggest that StT can significantly enhance running performance by improving key factors such as running economy, power, and endurance capacity (Gill, Williams, & Reifsteck, 2017). StT works by overloading the neuromuscular system, leading to better motor unit recruitment, increased firing frequency, musculotendinous stiffness, and improved intramuscular coordination, all of which contribute to enhanced running efficiency and performance metrics (Siddique et al., 2020; Škarabot, Brownstein, Casolo, Del Vecchio, & Ansdell, 2021).

Different modalities of StT, such as explosive and heavy StT, target various physiological adaptations. Explosive StT which includes bodyweight jumping and plyometric exercises, improves the rate of motor unit activation and muscular power (Liao et al., 2022). Although, heavy StT enhances anaerobic capacity and maximal speed is particularly useful for sprinting in competitive events (Gäbler, Prieske, Hortobágyi, & Granacher, 2018). These adaptations help delay fatigue and increase the MLDA's ability to sustain lower levels of exertion over time, which is critical for long-distance events (Midgley, McNaughton, & Jones, 2007).

Additionally, StT has been shown to improve haematological profiles, which are critical for endurance performance. Specifically, StT can increase red blood cell (RBC) counts, Hb, and Hct, all of which are essential for efficient oxygen delivery to working muscles (Ahmadizad & El-Sayed, 2005). While endurance training traditionally focuses on improving aerobic capacity, integrating StT offers a complementary approach, potentially boosting both muscular and haematological adaptations (Tomschi et al., 2018).

However, the specific effects of StT on the haematological profiles of elite runners remain underexplored (Zacháry et al., 2023). Existing research suggests that StT may positively influence these parameters, but further investigation is required to fully understand its impact, particularly in high-level MLDA (Tomschi et al., 2018). This study aims to fill this gap by examining how a structured StT program affects the haematological profiles, physiological adaptations, and overall performance of elite mid-to-long distance runners (Boullosa et al., 2020).

The study also explores the predictive role of pre-intervention Hb levels on post-StT outcomes, offering insights into how baseline physiological metrics may influence the effectiveness of StT interventions (Steiner, Maier, & Wehrlin, 2019). By addressing these factors, this research seeks to optimize training regimens for elite endurance MLDA, contributing to a more nuanced understanding of the relationship between ST, haematological adaptation, and performance improvement (Best, 2021; Mujika, Bourdillon, Zelenkova, Vergnoux, & Millet, 2024).

The effects of StT on endurance athletic performance have long been the subject of debate among athletes, coaches, and sports scientists. StT has a positive impact on middle- and long-distance running performance and its key determinants for different competitive levels (Blagrove, Howatson, & Hayes, 2018). StT modalities have been shown to elicit performance improvements in moderately-trained (Albracht & Arampatzis, 2013), well-trained (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Mujika et al., 2024), and highly-trained participants (Boullosa et al., 2020). This suggests that runners of any training status can benefit from ST.

StT provides an overload to the neuromuscular system, improving motor unit recruitment, firing frequency, musculotendinous toughness, and intramuscular coordination, potentially providing distance runners with a approach to enhance their RE and event-specific muscular power elements (Liao et al., 2022). StT includes both explosive and heavy ST, which promote different training adaptations (Aagaard & Andersen, 2010). Explosive StT involves bodyweight jumping exercises (Blagrove et al., 2018) and plyometric exercises, commonly used to increase short-tempered strength through the stretch-shortening cycle (Iaia & Bangsbo, 2010). This leads to adaptations such as an increased rate of activation of motor units (Coutts, Wallace, & Slattery, 2007).

StT contributes to enhancing endurance performance by improving the economy of movement, delaying fatigue, improving anaerobic capacity, and enhancing maximal speed. In running, the combination of these changes can provide an MLDA with tactical advantages, such as in attacks or final sprints, while also potentially affecting indices of aerobic capacity (Chen et al., 2023). Additionally, strength exercises that enhance endurance capacities are imperative in improving competitive running performance (Siddique et al., 2020; Škarabot et al., 2021).

The integration of StT into the regimen of endurance MLDA, particularly MLDA, has gained considerable attention due to its potential to enhance performance (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Mujika et al., 2024). StT not only augments muscular power and endurance but also induces beneficial physiological and haematological adaptations (Barnes & Kilding, 2015; Montero et al., 2017). Haematological parameters such as increased Hb concentration and RBC count have been associated with improved endurance capacity (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Schumacher, Schmid & Bültermann, 2002). The aim of this study is to examine the impact of a structured StT program on the haematological profiles, physiological adaptations, and performance metrics of elite mid-to-long distance runners. This study hypothesizes that StT modalities will show significant changes in MLDA haematological, physiological, and performance parameters, with RHR being the most affected physiological parameter. By addressing this gap in the literature, the study aims to provide a comprehensive understanding of how StT can be integrated into the training regimens of elite endurance MLDA to optimize performance (Steiner et al., 2019; Tomschi et al., 2018).

MATERIALS AND METHODS

Description of the sample population

This study was conducted in the Addis Ababa region of Ethiopia, focusing on an elite group of male middle- and long-distance athletes (MLDA) coached by the researcher. Participants were selected from athletes who primarily trained at high-altitude sites, including Intoto, Kenenisa's running tracks, and Dukum sand roads, with elevations ranging from 2,800 to 3,500 meters above sea level. These athletes were chosen due to their competitive status and representation of Ethiopia in international middle- and long-distance running events (1,500m to 10,000m).

Research design

This study employed a quasi-experimental design to investigate the effects of strength training on physiological and haematological factors influencing running performance. A purposive and convenience sampling technique was used to select 21 elite male MLDAs who met the inclusion criteria of competing at the national or international level.

Following a pre-test assessment, participants underwent a six-week strength training (StT) intervention, after which post-treatment effects on performance-related physiological and haematological determinants were evaluated. Ethical approval for the study was obtained from the Addis Ababa University College of Natural

Sciences Research Ethics Committee. All participants provided written informed consent, and the study adhered to the ethical principles outlined in the Helsinki Declaration for human research.

Experimental procedure

The intervention consisted of a six-week StT program, with 3–4 sessions per week. The study was conducted in three phases:

- Pre-test phase: Physiological and haematological parameters were assessed after four weeks of pre-intervention training.
- Intervention phase: A six-week StT program was implemented, focusing on endurance, strength, and speed training.
- Post-test phase: The same physiological and haematological parameters were measured immediately after the intervention.

The StT program included three hard training days, one moderate day, two easy days, and one rest day per week. Training variables (type, volume, and intensity) were strictly controlled, while extrinsic and intrinsic factors remained uncontrolled to minimize bias inherent in quasi-experimental designs

Strength training protocol

The StT program integrated hill running (3 × 200m) as the final station in a circuit of bodyweight exercises. The circuit comprised six sets of eight stations, with each station involving 1–2 minutes of work followed by a one-minute rest. Between sets, participants rested for three minutes. The program targeted muscle groups critical to running performance.

Training sessions were conducted three times per week (Tuesday, Thursday, and Saturday) over six consecutive weeks. Each session included: a 20-minute warm-up, 10 minutes of dynamic mobilization exercises, the main training session (duration determined by individual preliminary tests), and a 10-minute cool-down.

A preliminary test was conducted to establish each participant's workload, set at 60–80% of their one-repetition maximum (1RM). The program followed the principle of progressive overload, with workload increasing by 10% weekly until reaching 80% of 1RM.

Data collection techniques

Blood samples were collected 48 hours after the final training session of each intervention phase. For the pre-test, participants were advised to refrain from strenuous activity for two days prior to sample collection. A total of 10 mL of blood was drawn from the antecubital fossa vein after a 12-hour fast. Post-StT blood samples were collected following the same procedure. Blood collection and analysis were performed by trained professionals in a certified laboratory.

Physiological data were collected through event-specific time trials, indirect VO_{2max} tests, 400m speed tests, and RHR measurements. Pre- and post-StT data collection adhered to standard laboratory protocols and established guidelines (Mackenzie, 2005).

Data analysis

Descriptive statistics, including mean (M), standard deviation (SD), and range, were calculated for pre- and post-StT data to identify general trends. Paired t-tests were conducted to assess statistically significant changes in physiological, performance, and haematological variables from pre- to post-StT.

Correlation analysis was performed to explore relationships between variables, and Analysis of Variance (ANOVA) was used to determine statistically significant differences in dependent variables (e.g., VO_{2max}, 400m speed, 5,000m run-time, RBC count, WBC count, Hb, Hct) before and after the StT intervention. Multiple regression analyses were conducted to evaluate the predictive power of pre- and post-StT metrics on post-StT haemoglobin (Hb) levels. Statistical significance was set at $p < .05$.

RESULTS

Physiological adaptations

The analysis of resting heart rate (RHR) revealed a mean pre-intervention value of 53.14 ± 3.82 beats per minute (bpm). Following the post-strength training intervention (PSTI), the mean RHR increased slightly to 54.10 ± 4.02 bpm. A paired t-test comparing pre- and post-StT RHR values (t = -1.00, *p* = .33) indicated no statistically significant change (Table 1).

For VO_{2max}, the pre-StT mean value was 78.37 ± 2.10 mL/kg/min, which increased marginally to 79.33 ± 4.70 mL/kg/min post-StT. The paired t-test revealed no statistically significant improvement in VO_{2max} (t = -1.11, *p* = .28) following the intervention (Figure 1).

In contrast, the 5000m running performance showed a notable improvement. The average time to complete the 5000m run decreased significantly from 13.78 ± 0.28 minutes pre-StT to 13.51 ± 0.03 minutes post-StT. A paired t-test demonstrated a statistically significant improvement in performance (t = 4.37, *p* = .0003), indicating a meaningful enhancement in running efficiency following the intervention.

The analysis of RHR revealed that before the intervention the mean RHR with a standard deviation (SD) was (53.14 ± 3.82) beats per minute (bpm). Post-strength training intervention (PSTI), the mean RHR increased slightly to 54.10 bpm (±4.02). A paired *t*-test comparing pre-and post-StT RHR yielded (*t* = -1.00, *p* = .33), indicating no statistically significant change (Table 1).

Table 1. The summary table of pre–post analysis.

Metric	Pre Mean	Post Mean	Change (%)	t	*p*	Cohen's d
Resting Heart Rate (bts/sec)	53.1	54.1	1.79	-1.0	.33	0.24
12-minute run (m)	4010.5	4017.1	0.17	-0.88	.39	0.07
VO_{2max} (mL/kg/min)	78.372	79.3	1.22	-1.11	.28	0.26
Speed test (sec)	57.079	55.8	-2.24	5.45	.00**	-0.54
Red Blood Cells (million/µL)	5.447	5.56	2.08	-2.48	.02*	0.3
White Blood Cells (WBC)	7.428	7.52	1.23	-1.06	.3	0.05
Hemoglobin (g/dL)	15.94	16.15	1.34	-2.49	.02*	0.21

*Note. Key: t-statistic (t), p-value (p), '**' sig.at 99% CI, and effect size (Cohen's d).*

For VO_{2max}, the pre-StT mean was 78.37 mL/kg/min (±2.10), which increased slightly to (79.33 ± 4.70 mL/kg/min) post-StT. The paired *t*-test resulted no significant improvement in VO_{2max} (*t* = -1.11, *p* = .28), post-StT (Figure 1).

In contrast, the 5000M showed a notable improvement. The average time to complete the 5000m run decreased from 13.78 minutes (±0.28) pre-StT to 13.51 minutes (±0.03) post-StT. A paired *t*-test revealed a statistically significant improvement in performance, (*t* = 4.37, *p* = .0003).

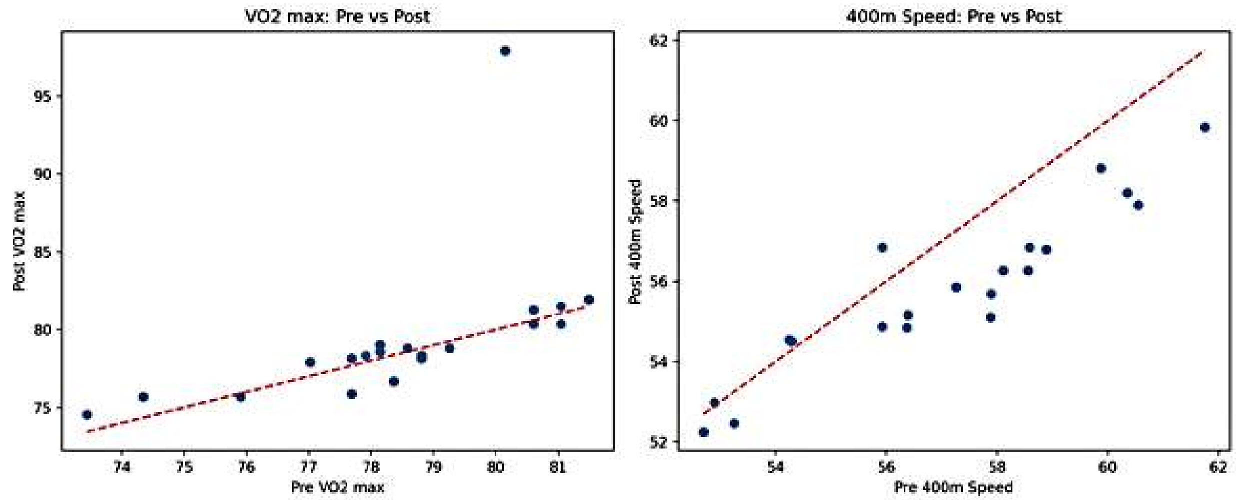

Figure 1. Linear regression.

Haematological changes

The intervention influenced several haematological parameters, as analysed through a violin plot (Figure 2). The post-StT result exhibited a slightly higher RBC mean count compared to the pre-StT, but with greater variability, as evidenced by the wider distribution. However, the ANOVA test indicated no significant impact of the intervention on RBC (p = .061).

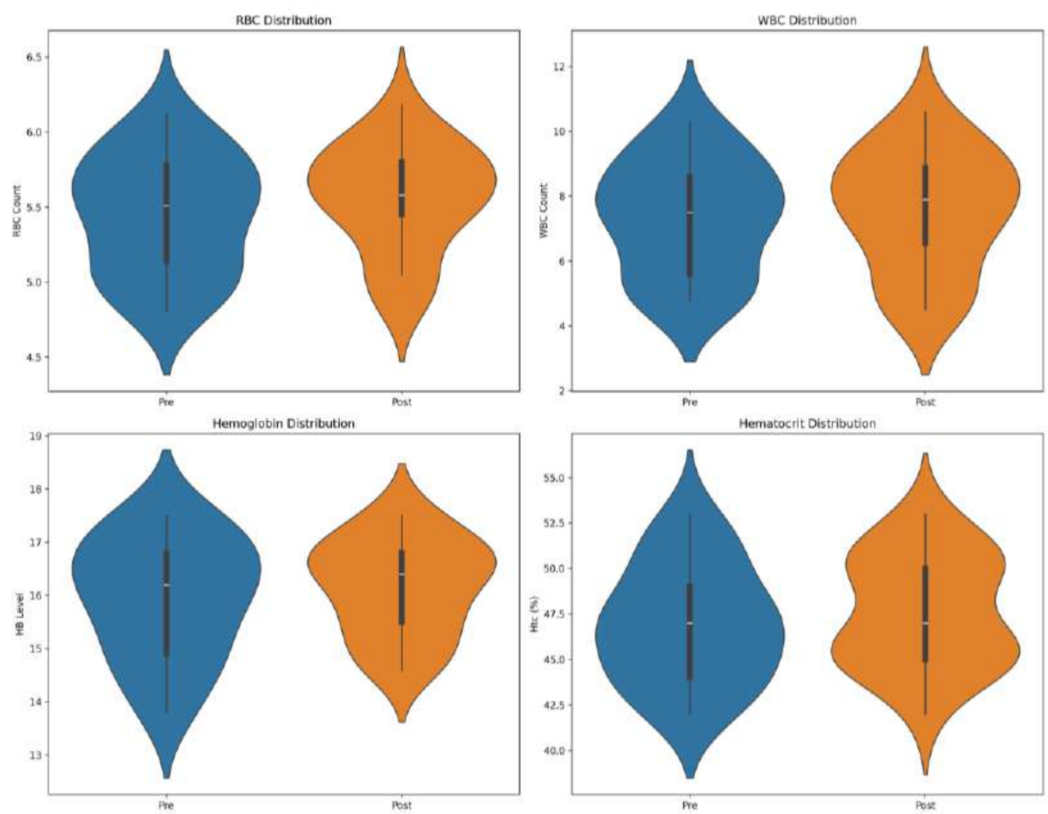

Figure 2. Statistical summaries of haematology.

PSTI, the Hb level showed a noticeable decline compared to pre-StT, as indicated by the violin plot (Figure 2). The variability in Hb levels was slightly lower post-StT. Regression analysis revealed a significant relationship between pre- and post-StT Hb levels (R^2 = 0.899, p < .001), but the ANOVA test confirmed no significant treatment effect (p = .158, Table 1). The mean WBC count remained similar between the pre- and post-StT groups. However, the distribution in the post-StT group was more concentrated around the median, indicating reduced variability. Regression analysis demonstrated a strong relationship between pre-StT and post-StT WBC counts (R^2 = 0.892, p < .001) and in RBC (R^2 = 0.848, p < .001) (Figure 3), but the ANOVA test showed no significant change in RBC (p = .218, Table 1).

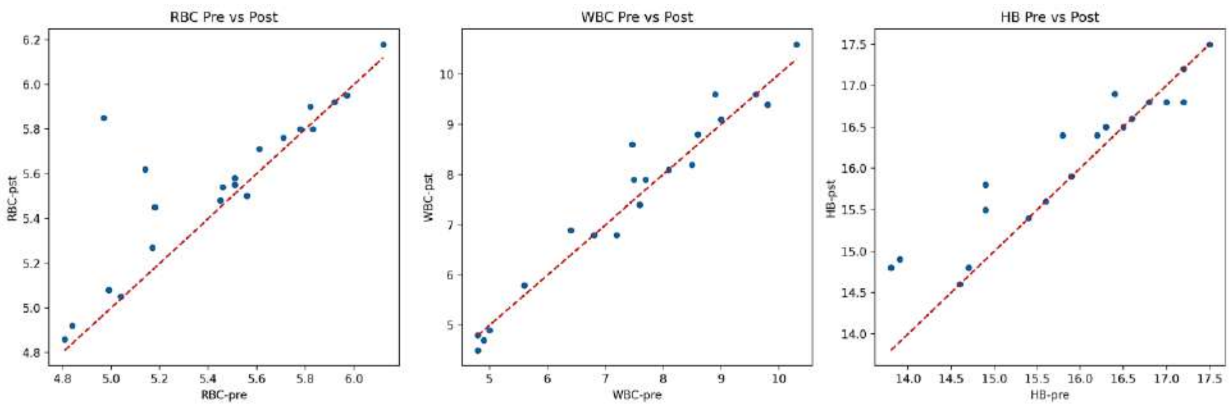

Figure 3. Linear regression of pre by post intervention.

Measures of association between anthropometry and strength training intervention (STI)

ANOVA results demonstrated a significant association between RBC count and age (F = 3.167, Eta² = 0.68, p = .03), with age explaining 19.3% of the variance and linearity being an important factor (p = .02) (Table 2).

Table 2. Summary of Post-haematological parameters.

Parameter	Variable	Between SS	Within SS	Total SS	F-Value	p	R²	Eta²
RBC	Age	3.2	1.5	4.7	3.17	.03	0.19	0.68
	Height	3.2	1.5	4.7	1.73	.21	0.13	0.68
	Weight	1.3	3.4	4.7	1.17	.40	0.06	0.28
WBC	Age	39.9	33.5	73.4	1.79	.17	0.07	0.54
	Height	25.2	48.2	73.4	0.43	.90	0.11	0.34
	Weight	18.1	55.3	73.4	0.98	.50	0.01	0.25
HB	Age	2.7	15.1	17.8	0.27	.96	0.02	0.15
	Height	12.1	5.8	17.8	1.72	.20	0.00	0.68
	Weight	1.0	16.8	17.8	0.19	.96	0.00	0.06
Htc	Age	88.9	97.2	189.0	1.33	.32	0.06	0.47
	Height	91.8	97.2	189.0	0.77	.70	0.07	0.49
	Weight	4.7	184.2	189.0	0.08	1.00	0.01	0.03
RHR	Height	247.1	76.7	323.8	2.64	.10	0.00	0.76
	Weight	108.1	215.7	323.8	1.50	.25	0.02	0.33

Note: Sum of Squares (SS), degree of freedom (df), Mean Square (M^2), estimated association (Eta),sig. at 95% CI (p)

No significant effects of age were observed for WBC, Hb, or Hct. RHR by height has high effect sizes (Eta² = 0.76) but is not statistically significant (p = .10). Height was marginally associated with RHR (F = 2.637, p

= .078), but no significant associations were observed between height and the haematological parameters. WBC by height show moderate effect sizes (Eta² = 0.54). Similarly, weight showed no significant effects on any of the studied parameters.

The data suggest that the intervention had limited significant effects across most parameters. While the 5000M showed a marked improvement, the haematological parameters and VO_{2max} remained largely unchanged. We found strong negative correlation (-0.71) between VO_{2max} and TT, Figure 4.

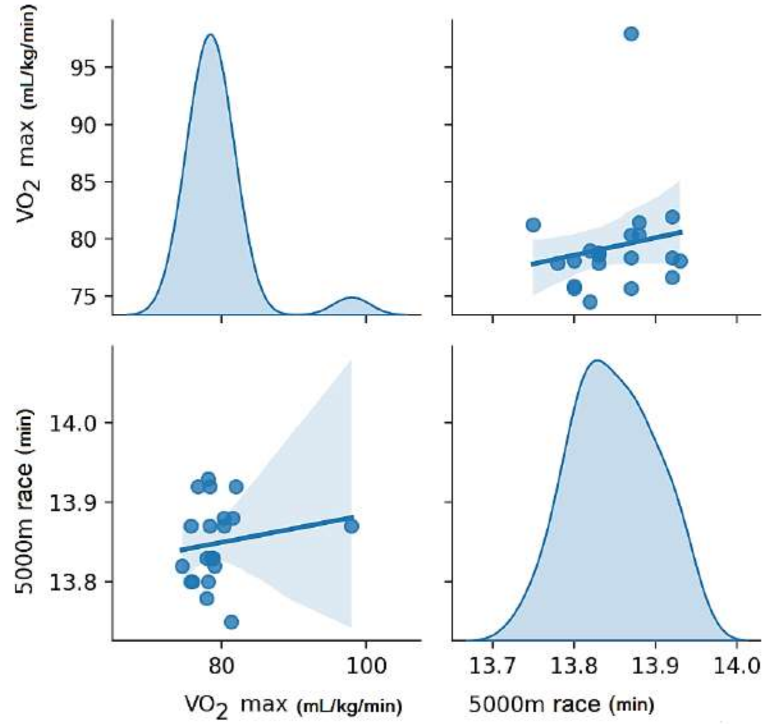

Figure 4. The relationships between key predictor.

DISCUSSION

The absence of significant change in RHR following the intervention aligns with findings from Thompson (Thompson, 2017), which reported that short-term exercise, particularly at moderate intensity, often does not alter RHR. This stability in RHR is consistent with our results, suggesting that the intervention had no significant impact on this variable.

The lack of significant change in VO_{2max} supports the observations of Sindall, who noted that improvements in VO_{2max} typically require longer training durations (Sindall, 2020). The short-term nature of this intervention was insufficient to produce a statistically significant difference in VO_{2max}, consistent with other finding (Saunders, Pyne, Telford, & Hawley, 2004).

The moderate R^2 (0.304) indicates that VO_{2max} is influenced by various factors, with the intervention showing a significant effect (*p* = .0096). Strong negative correlation between VO_{2max} and 5000M indicates better cardio fitness leads to faster times. This finding aligns with Sindall, who noted that VO_{2max} is a key predictor of long-distance performance (Sindall, 2020). However, the moderate R^2 suggests other factors, such as genetics or long-term adaptations, also play a role. The significant 5000M reduction in post-StT is in line with the study, which demonstrated that short-term interventions can improve distance running performance (Ives, Du, Etter, & Welch, 2005).

This result highlights the immediate performance benefits from the StT, reflecting enhanced running speed. The R^2 of 0.719 shows a strong predictive relationship between variables of pre-StT and TT. The significant treatment effect (p = .003) confirms the intervention's impact on performance. This aligns with similar study results (Das, 2013; Sindall, 2020), emphasized on the importance of VO_{2max} and aerobic capacity in long-distance running. The high R^2 (0.784) indicates a strong relationship between pre-StT variables and post-StT 400m speed test. The improvement in post-StT speed test, supported by comparable study (Raghuveer et al., 2020), highlights the role of both aerobic and anaerobic endurance in short-distance performance. Ethiopian MLDA' enhanced 400m speed is likely linked to improved cardiovascular fitness and training adaptations.

Age significantly influenced RBC post-StT, aligning with similar study that suggested age-related changes in haematopoiesis affect erythrocyte levels (Sheykhlouvand et al., 2018). However, no significant effects were observed for WBC, Hb, or Hct, consistent with study, which reported that these parameters are less sensitive to age (Bassett & Howley, 2000). The high R^2 (0.927) indicates that pre-intervention RBC levels strongly predict post-StT. However, the lack of significant change (p = .061) suggests that the intervention did not substantially affect RBC count, consistent with Mandić (2022) who found that significant changes in RBC often require longer training periods. Height showed marginal significance for RHR but no significant effect on RBC, WBC, Hb, or Hct, in line with the mixed findings in the literature. Some studies, suggest height influences cardiovascular metrics (Parmar, Jones, & Hayes, 2021), while others, show minimal direct effects (Rodríguez Zamora, 2013). The indirect influence of height, possibly mediated through body composition, is supported by (Liao et al., 2022; Tomschi et al., 2018). The R^2 of 0.892 reflects a strong relationship between pre- and post-StT WBC levels. The non-significant treatment effect (p = .218) is expected, as WBC counts are generally stable and less responsive to short-term endurance training (Nieman & Pence, 2020). Contrary to previous studies, weight did not significantly influence the haematological parameters (Sitkowski, Klusiewicz, Pokrywka, Jankowski, & Malczewska-Lenczowska, 2023). This discrepancy may be due to the lack of body fat percentage or distribution measurement, as highlighted by Nybo et al. (2010) which may better capture the relationship between weight and physiological outcomes. The stability of RBC and WBC measurements over time is supported by the previous findings (Koç, Özen, Abanoz, & Pulur, 2018), who reported minimal variation in these parameters after short-term exercise interventions.

The R^2 of 0.899 suggests that pre-StT Hb levels predict post-StT levels. The lack of significant treatment effect (p = .158) indicates that short-term interventions may not significantly alter Hb levels, consistent with similar works, who noted that Hb changes require longer training periods (Mandić, 2022; Wang et al., 2017). The R^2 of 0.894 indicates a strong relationship between pre-StT and post-StT Hct levels. The non-significant treatment effect (p = .061) suggests that short-term interventions may not substantially alter Hct, consistent with RBC and Hb findings.

CONCLUSION

This study underscores the impact of strength training (StT) on running performance, evidenced by significant improvements in 5000m run time and 400m speed, among elite male MLDA. The StT led to measurable improvements in running performance, its effects on physiological measures like RHR and Maximal oxygen consumption (VO_{2max}) were not statistically significant. Additionally, the intervention did not result in significant changes in haematological markers such as RBC, WBC, and Hb, likely due to the relatively short duration of the study.

The study suggests that while StT is effective in enhancing athletic performance, longer interventions may be necessary to elicit significant haematological adaptations. Short-term exercise can improve performance metrics while maintaining stability in physiological measures such as RHR and VO_{2max}. This study highlights the importance of baseline measures in determining exercise-related changes and supports the focus on pre-exercise blood metrics for predicting post-StT outcomes.

Future research should explore additional factors such as body composition and long-term training effects to provide a comprehensive understanding of the relationships. Moreover, studies should focus on extended training periods and incorporate a larger sample size to further investigate the long-term effects of StT on both performance and haematological parameters in elite runners.

AUTHOR CONTRIBUTIONS

Nigatu Worku conceptualized the study, conducted the literature review, designed the experiment, performed measurements and data analysis, and drafted the original manuscript. Aschenaki Taddese and Zeru Bekele contributed to the experimental design, provided supervision, assisted with visualization, and conducted the final review. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors. The experiments comply with the current laws of the country in which they were performed. The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.

INSTITUTIONAL REVIEW BOARD STATEMENT

The Ethical Committee of the Addis Ababa University, Ethiopia has granted approval for this study on 07 January 2023.

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ORIGINAL ARTICLE

Anthropometric profile of female basketball players: The influence of competitive level and playing position

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ABSTRACT

This study aimed to analyse the anthropometric characteristics of female basketball players, focusing on competitive level and specific playing position. The sample included 62 female basketball players from teams across all senior women's basketball leagues in Spain, (1st to 4th division). Different anthropometric measurements were evaluated to evaluate body composition and somatotype. Significant differences emerged between competitive levels, with higher-level players showing more favourable results in some measures. Furthermore, a distinctive profile was identified based on playing position: centers were generally taller, heavier and had higher percentages of body fat and muscle mass compared to forwards and guards. This study provides valuable information on the physical attributes of female basketball players across competitive levels, improving knowledge of the demands of current women's basketball.
Keywords: Performance analysis, Anthropometric profile, Female basketball, Somatotype.

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INTRODUCTION

In sports today, performance depends on a number of variables, including anthropometric characteristics, physical fitness, psychological traits and sport-specific skills (Campa et al., 2019). Specifically in team sports, performance is greatly influenced by conditional factors, technical-tactical skills, and the physical characteristics of the athletes (Drinkwater et al., 2008). Achieving optimal sports performance requires a connection between the different skills that player have to execute, since they have to perform a large number of high-intensity actions during the offensive and defensive phases (Gryko et al., 2022). Therefore, it's essential to understand how the anthropometric characteristics in basketball, in addition to checking whether these evolve along with the technical-tactical development of the players.

The physical characteristics of the players show the reality of the athlete, being a mixture that involves morphological features, physical fitness and technical-tactical skills (Köklü et al., 2011). Among all these factors, morphological characteristics are essential for the evaluation and selection of players (Vaquera et al., 2015). Furthermore, the scientific literature states that both anthropometric characteristics and somatotype profiles are recognized as performance predictors (Ostojic et al., 2006). In addition, anthropometric characteristics such as fat percentage, skin fold thickness, height, span and diameters are relevant in elite basketball players, making them indicators of highly competitive level (Vaquera et al., 2015).

These characteristics are worth mentioning because they affect the playing position and the roles that players play within their teams. In women's basketball, for example, players who have greater speed of movement or greater agility tend to play positions further away from the rim, while taller or more corpulent players tend to play closer to the rim (Cui et al., 2019). Historically, literature has categorized basketball positions into three (guard, forward, and center) or five (point guard, shooting guard, small forward, power forward, and center) roles, each defined by a combination of physical, technical, and tactical factors (Ibáñez et al., 2018).

In recent years, basketball has undergone major changes in technical-tactical demands in addition to physical demands (Ibáñez et al., 2018). The higher the level of competition, the greater technical-tactical and physical demands. Consequently, analysing basketball players by competitive level and specific position is crucial. While some players may adapt to multiple positions, it is essential to assess them according to their primary role on the court (Vaquera, 2008). Additionally, understanding the evolution of anthropometric profiles in women's basketball is important, as it aids in talent identification and performance differentiation (Ziv & Lidor, 2009). Therefore, this study aimed to analyse the anthropometric characteristics of female basketball players to determine the influence of playing position and competition level on these attributes.

MATERIALS AND METHODS

Subjects

The study involved 62 active female basketball players from Spain's four senior women's divisions during the 2023/24 season. Players were divided by category (Table 1) and position (Table 2). To facilitate analysis, the leagues were grouped into three categories: First Division (1st; n = 12, training 16.0 ± 1.0 hours per week), Second and Third Divisions combined (2nd–3rd; n = 22, training 16.0 ± 3.5 hours per week) and Fourth Division (4th; n = 28, training 6.8 ± 1.1 hours per week) (Table 1). This grouping allowed for a distinction between fully professional (1st), semi-professional (2nd–3rd), and amateur players (4th). All participants were informed about the study's benefits and risks, and each provided written consent. The study was approved by the Ethics Committee of the Universidad de León (Code: ETICA-ULE-004-2021).

Players were classified into three positions (guards, forwards, and centers) (Table 2) following the criteria of Salgado et al. (2009) as it remains a relevant method for classifying positions in women's basketball.

Table 1. Descriptive characteristics of the players based on their category.

	1st (n = 12)	**2nd-3rd (n = 22)**	**4th (n = 28)**	**Total (n = 62)**	**F**	***p***
Age (years)	25.1 ± 2.2[a]	23.6 ± 4.8[a]	19.3 ± 1.9	21.7 ± 2.9	13.461	.001
Height (cm)	179.4 ± 8.7[a]	179.7 ± 12.3[a]	170.7 ± 6.7	175.1 ± 8.8	6.172	.004
Body mass (kg)	71.6 ± 8.0	73.1 ± 8.9[a]	65.3 ± 8.4	68.9 ± 8.5	4.830	.012

Note. 1st = First Division; 2nd-3rd = Second and Third Division; 4th = Fourth Division; a = significant differences with 4th; Significance level p = <.05.

Table 2. Descriptive characteristics of the players based on their specific playing-position.

	G (n = 16)	**FW (n = 31)**	**C (n = 15)**	**Total (n = 62)**	**F**	***p***
Age (years)	20.3 ± 3.7	22.4 ± 5.6	22.6 ± 3.7	21.7 ± 2.9	46.431	.372
Height (cm)	165.2 ± 3.0[a,b]	176.1 ± 6.9[a]	184.3 ± 5.7	175.1 ± 8.8	17.612	.001
Body mass (kg)	60.3 ± 4.5[a,b]	68.9 ± 6.3[a]	77.3 ± 8.9	68.9 ± 8.5	1.053	.001

Note. G = Guards; FW = Forwards; C = Centers; a = significant differences with C; b = significant differences with FW; Significance level p = <.05.

Data collection

Anthropometric measurements followed the International Society for the Advancement of Kinanthropometry (ISAK) protocols and were conducted in a standardized environment with controlled lighting and temperature. All measurements were performed by the same trained and ISAK-certified evaluator to ensure consistency and minimize measurement variability. Data collection occurred between 10:00 and 12:00 a.m., with players arriving fasted and refraining from physical activity the day prior. The collected data included height, body mass, seven skinfolds (triceps, subscapular, biceps, suprailiac, abdominal, anterior thigh, medial calf), three diameters (humeral biepicondylar, wrist biestylion, femoral biepicondylar), and four circumferences (relaxed arm, flexed and contracted arm, mid-thigh, calf) (Alvero et al., 2010). The instruments used were a Surface Precision 9400 Full Healthy scale (0–180 kg; precision: 100 grams), a stadiometer (precision: 1 mm), a Harpenden skinfold calliper (0–80 mm; precision: 0.2 mm), a small anthropometer (precision: 1 mm), and an anthropometric measuring tape (0–100 cm; precision: 1 mm).

Body composition was analysed following Salgado et al. (2009), using a four-component model: 1) fat percentage, calculated with Faulkner's equation (1968) based on six skinfolds; 2) bone mass, estimated with the modified Von Dobeln formula by Rocha (1974); 3) residual mass, based on Würch's constants (1974); and 4) muscle mass, calculated with Lee's formula (2000). Somatotype was determined using the Heath-Carter anthropometric method (Campa et al., 2020).

Statistical analysis

Descriptive statistics (mean ± standard deviation) were calculated for each variable. A one-way ANOVA with a 95% confidence interval was used to assess differences across competitive levels and playing positions, followed by the Scheffé post-hoc test to identify specific group differences. Statistical significance was set at $p < .05$. Analyses were conducted using SPSS software (Version 26.0; IBM Corp., Armonk, NY, USA).

RESULTS

Significant differences were found across competitive levels in key anthropometric and body composition variables. Players in higher competitive categories were generally older, taller, and heavier compared to those in lower divisions (Table 1). Muscle mass percentage was highest among players in the First Division, with additional significant differences observed in bone mass across divisions (Table 3). No significant differences in body fat percentage were identified by competitive level.

Table 3. Descriptive characteristics of the body composition of basketball players based on their category.

	1st	2nd-3rd	4th	F	*p*
% Body fat	15.2 ± 2.8	17.7 ± 3.9	18.2 ± 3.7	2.28	.111
% Muscle mass	45.5 ± 3.0[a]	42.8 ± 4.2[a]	38.7 ± 3.6	93.48	.001
% Bone mass	21.7 ± 1.5[a]	19.9 ± 1.2[a]	20.2 ± 1.4	7.94	.001

Note. 1st = First Division; 2nd-3rd = Second and Third Division; 4th = Fourth Division; a = significant differences with 4th Level of significance p = <.05.

Differences were also observed in player characteristics based on specific playing positions. Centers were the tallest and heaviest, followed by Forwards, while Guards presented the lowest values in height and body mass (Table 2). Muscle mass percentage was highest for Centers and lowest for Guards (Table 4). No significant differences in body fat percentage were found across positions, although Centers showed slightly higher values than other positions.

Table 4. Descriptive characteristics of the body composition of basketball players based on their specific playing-position.

	G	FW	C	F	*p*
% Body fat	16.2 ± 3.3	17.0 ± 3.5	18.6 ± 4.8	1.088	.344
% Muscle mass	40.5 ± 3.3[a,b]	42.8 ± 2.9[a]	45.2 ± 3.1	1.709	.001
% Bone mass	19.4 ± 1.8	20.6 ± 1.9	21.2 ± 1.6	24.22	.190

Note. G = Guards; FW = Forwards; C = Centers; M = Mass; a = significant differences with C; b = significant differences with FW; Level of significance p = <.05.

In terms of somatotype, no significant differences were found among competitive levels (Table 5). By playing position, Guards showed a higher mesomorphic component compared to the other playing positions, with no significant differences in the endomorphic and ectomorphic components among playing positions (Table 6).

Table 5. Descriptive characteristics of the somatotype of basketball players based on their category.

	1st	2nd-3rd	4th	F	*p*
Endomorph	3.32 ± 0.31	3.02 ± 0.89	3.66 ± 0.75	2.98	.059
Mesomorph	3.62 ± 1.22	2.73 ± 1.44	3.14 ± 0.69	0.218	.805
Ectomorph	2.42 ± 0.60	2.19 ± 0.94	2.05 ± 0.60	0.242	.786

Note. 1st = First Division; 2nd-3rd = Second and Third Division; 4th = Fourth Division.

Table 6. Descriptive characteristics of the somatotype of basketball players based on their specific playing-position.

	G	FW	C	F	*p*
Endomorph	3.3 ± 0.0	3.21 ± 0.92	3.64 ± 1.01	0.219	.804
Mesomorph	3.49 ± 0.88[a]	2.71 ± 1.10	2.33 ± 1.24	5.870	.005
Ectomorph	1.92 ± 0.62[a]	2.30 ± 0.79	2.38 ± 0.82	3.225	.470

Note. G = Guards; FW = Forwards; C = Centers; M = Mass; a = significant differences with C; b = significant differences with FW; Level of significance p = <.05

DISCUSSION

The primary aim was to analyse the anthropometric characteristics of female basketball players by competitive category and playing position. A key finding has been the presence of distinct anthropometric differences based on competition level. Height and weight, frequently highlighted in the literature on basketball player body composition (Cabarkapa et al., 2024; Dominguez-Navarro et al., 2023), were significantly greater in higher-level players. Players in the First and Second-Third Divisions were both taller and heavier than those in the Fourth Division (Table 1), suggesting that these parameters play an essential role in player selection across competitive levels.

In terms of body composition, muscle mass percentage was highest in First Division players, followed by Second-Third Division and then Fourth Division players. These finding are similar to those found in the scientific literature (Casajaús & Aragonés, 1997; González de los Reyes et al., 2020), which suggest that an increase in competition demands my contribute to an improvement in the development of muscle mass thought more specialized training focused on performance (Fox et al., 2018). However, no significant differences were observed between categories when assessing body fat. Players at higher levels shower a tendency towards a lower percentage of fat, probably influenced by the number of sessions performed by the players. The results of our study are similar to those reflected in other studies, which indicate that female basketball players had an average percentage of fat mass of 18% (Bayios et al., 2006).

Height also had a positive correlation with competitive level, which is directly related to previous studies in which it can be observed how taller players competed in higher leagues (Rodríguez-Alonso et al., 1998; Bayios et al., 2006; Salgado et al., 2009). Similar to this, we found a study of regional level U-19 players, which shows height data similar to those found in fourth division players, reinforcing this trend (Rodríguez-Fernández et al., 2023).

In relation to playing positions, centers were the tallest and heaviest players, followed by forwards, with guards being the shortest and lightest. This is in line with findings from other studies where height is given a major factor for center and forwards due to the competitive demands seen in the game (Köklü et al., 2011; Ostojic et al., 2006). Body composition data revealed that centers had the highest muscle mass percentage, with guards showing the lowest. Although fat mass differences were not significant between positions, centers had slightly higher fat percentages, something that is due to their competitive demands, as these players develop their game closer to the rim (Ferioli et al., 2018), which can help to gain a certain advantage in body-to-body actions (Ackland et al., 1997; Erculj et al., 2009). However, this may also negatively impact performance in other variables related to high-intensity actions (Gil et al., 2014). Looking at specific playing positions, the players who in our study had the lowest height and percentage of fat were the guards. This can also be observed in the studies by Moncef et al. (2012) and Ostojic et al. (2016), where the guards have a low height and percentage of fat, making them explosive players with a better performance in speed and agility test.

Regarding somatotype, the first division players had predominantly mesomorphic profiles, while the players from the other divisions had a predominantly endomorphic somatotype, similar results to those found in the study by Salgado et al. (2009). If we now focus on the specific playing position, the guards had a mesomorphic profile, while the forwards and centers showed an endomorphic profile, which also supports previous findings (Salgado et al., 2009).

In recent years, basketball has evolved significantly in all its aspects (Mancha-Triguero et al., 2021). Comparing the current data with that of players from 15 seasons ago, with similar teams and leagues, it could be observed that today's players are generally shorter and less corpulent, however they have a higher muscle mass, which suggest a change in physical tendency since the 2007/08 season (Salgado et al., 2009).

CONCLUSIONS

In summary, our results identified significant differences in both body composition and somatotype component according to competitive level and playing position in female basketball players. In addition, we observed an evolution in the characteristics of female basketball players, with today's players being shorter and lighter but with greater muscle mass. Finally, it's important to recognise the individual characteristics of the players according to the level at which the compete and the playing position they play, as it's crucial for the improvement of talent selection programmes as well as improving individualised training strategies for basketball players.

AUTHOR CONTRIBUTIONS

Introduction, E.F.-G. and A.R.-F.; methodology, E.F.-G. and J.A.R.-M.; results, A.R.-F. and A.V.; discussion, E.F.-G., A.R.-F., J.A.R-M.; conclusions, A.V. and E.F.-G.; writing-writing of the original draft, E.F.-G.; writing-revising and editing, J.A. R.-M., A.V. and A. R.-F.

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ORIGINAL ARTICLE

The response of reaction time and fatigability to exhaustive exercise in young male

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ABSTRACT

The post-exercise effect on cognitive function is associated with exercise intensity, duration, and psychological and physiological factors. The present study aimed to investigate the impact of exhaustive exercise on cognitive function and the differences in psychological and physiological parameters between positive and negative responders to exercise. Seventeen young males performed an exhaustive incremental submaximal exercise task. Reaction time in the incongruent Stroop task, salivary cortisol and immunoglobulin A (SIgA) levels, and visual analogue scale scores for fatigue were evaluated. Participants were divided into 2 groups: slower group, which exhibited an increase in reaction time; and faster group, which exhibited a decrease in reaction time after the exercise. There were no differences in changes in the salivary cortisol and SIgA level between the slower and faster groups. The slower group exhibited a greater increase in fatigue than the faster group. The increase in fatigue score was positively correlated with the changes in reaction time. Results of this study demonstrated that the excessive increase in fatigue after exhaustive exercise delays cognitive response time. Findings suggest that the individual differences in perceived fatigability, rather than physiological responses, may be modulated to alter cognitive performance after exhaustive exercise.
Keywords: Performance analysis, Fatigue, Executive function, Exercise.

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INTRODUCTION

Cognitive function is believed to be critical for functional mobility in various decision-making and problem-solving processes, helping athletes and elderly to maintain sports performance and health-related quality of life (Williams et al., 2010). Recent studies have examined the responses of cognitive function to exercise (Basso & Suzuki, 2017, Chang et al., 2012). In general, moderate-intensity exercise has positively affects cognitive function (McMorris & Hale, 2012). In contrast to moderate exercise, the impact of high-intensity or exhaustive exercise cannot be confirmed because consistent results have not been obtained. Some studies have shown that high-intensity exercise that induces the accumulation of lactate decreases attention and lowers working memory score (Coco et al., 2019; Perciavalle et al., 2015). Another study reported that exhaustive exercise until exhaustion did not alter accuracy or reaction time in the Go/No-go test (Sudo et al., 2017). A study focusing on athletes reported that exhaustive exercise increased arousal status and shortened reaction time in the Flanker task (Vrijkotte et al., 2018). These discrepancies may be the results of differences in exercise intensity and duration, and individual differences in physiological response and psychological perspective(s) (Tomporowski & Norman, 1986).

Accumulation of physical and emotional fatigue is believed to lead to the deterioration of cognitive function (Barnes & Van Dyne, 2009). The degree of fatigue is modulated by the interaction between performance fatigability and perceived fatigability-related central, peripheral, psychological, and homeostatic factors (Enoka & Duchateau, 2016). Interestingly, Jager et al. (2014) reported a positive effect of exercise on the cognitive function evaluated by the conflict Flanker task only in cortisol responders who exhibited an increase in cortisol levels after the exercise game, whereas no changes were observed in non-responders who exhibited no increase or a decrease in cortisol levels after the exercise. This study suggests that the individual differences in homeostatic responses to exercise likely involved in enhancing of cognitive function. Furthermore, most previous studies investigating maximal exercise were conducted using incremental exercise protocols, which are confounded by the effect of high intensity or cumulative fatigue, and little is known about the exhaustion under submaximal exercise (Schmit et al., 2015). Recently, Hou et al. (2016) demonstrated that submaximal exercise until exhaustion induces central fatigue and alters brain activation patterns during hand movement. However, the effects of exhaustive exercise at submaximal intensity on cognitive function have not been investigated.

As such, the current study aimed to investigate the impact of exhaustive exercise on cognitive function along with homeostatic factors, such as stress and immune function, and the self-reported subjective response to exhaustive exercise in young males. We hypothesized that changes in cortisol or immunoglobulin A (SIgA) and perceived fatigability after exercise are higher in negative effects of exercise than in positive effects on cognitive function. Accordingly, we evaluated salivary cortisol and SIgA levels, visual analogue scale (VAS) score for fatigue, arousal, and sleepiness, and reaction time in the incongruent Stroop task before and after prolonged exhaustive exercise at submaximal intensity. We compared these parameters between positive responders, who exhibited faster reaction time, and negative responders, who exhibited slower reaction time after exercise.

MATERIALS AND METHODS

Subjects

Seventeen healthy young males (mean [±SD] age, 29 ± 3 years; height, 172 ± 7 cm; weight, 69 ± 8 kg) participated in this study. The subjects were medication-free and had no history of neurological or cardiovascular disease(s) or physical injuries. All participants were informed of the purpose and methods as well as the risks of the study, and each provided informed consent for participation. This study was performed in accordance with the principles of the Declaration of Helsinki and approved by the ethics committees of the Japan Institute of Sports Sciences (030).

Study protocol

Participants performed a cognitive task before and after exhaustive exercise in the afternoon. They were at least 3 h postprandial, abstained from caffeine and alcohol for 12 h, and strenuous exercise for 24 h. They underwent a graded exercise test using a cycle ergometer (Fujin-Raijin, O.C. Labo, Tokyo, Japan) until exhaustion based on a previous study that affects to brain function (Hou et al., 2016). The exercise started at 50 W as a warm-up for 5min; the workload was increased by 50 W every 8 min up to 250 W at the final stage, and they were encouraged to pedal until reaching an exhaustion state that could not maintain a cadence of 50 revolution per min. During the exercise test, heart rate was measured using a commercially available monitor (V800; Polar Electro Inc., Kemple, Finland) and oxygen uptake was measured using a spirometer (AE300S; Minato Medical Sciences, Osaka, Japan). These physiological parameters were averaged every 30 s, and the peak heart rate and maximal oxygen uptake were calculated. The present study recorded ratings of perceived exertion (RPE) using the Borg scale. Before and after exhaustive exercise, VAS score was measured, and salivary samples were collected to evaluate cortisol levels and SIgA secretion rate before and after exhaustive exercise.

Measurement

Cognitive function

Subjects performed the Stroop task, which is widely used to measure the ability to properly control attention and behaviour during executive tasks. The Stroop task involved incongruent condition as previously described in our laboratory (Akazawa et al., 2019). In the incongruent Stroop task, a colour word was displayed in incongruent colours (e.g., the word “*RED*” was presented in blue colour) at the top of the monitor and incongruent colour word on the right and left side of the monitor. Subjects were asked to identify the corresponding colours by pressing a button. This task included 2 sets of 10 trials, each set with a length of 30 s. Three practice sessions (1 week, 1 day and immediately before the experiment) were performed. The reaction time for correct answers were evaluated.

Psychological and physiological parameters

Before and after the exhaustive exercise, subjects were asked to report their subjective perceptions of fatigue, arousal, and sleepiness based on a VAS score, and saliva samples were collected. Each VAS item was scored from 0 mm (do not feel at all) to 100 mm (completely feel fatigue, arousal, or sleepiness) on a horizontal line. Saliva was collected using an oral cotton swab and a storage tube (Salimetrics oral swab; Salimetrics, Carlsbad, CA, USA). The subject sat, rinsed their mouth 3 times, and rested for at least 5 min. Saliva production was stimulated by chewing on cotton for 1 min. The obtained saliva was centrifuged (1500 ×*g*) and frozen at –80°C until analysis. Cortisol and SIgA concentration were determined using a commercially available enzyme immunoassay kit (Salimetrics, Carlsbad, CA, USA). The SIgA secretion rate was normalized to the saliva flow rate.

Statistical analysis

All data are expressed as mean ± standard deviation (SD). To assess the difference in response to the exhaustive exercise test, subjects were divided into the 2 groups: negative responders, who increased (slower group): and positive responders, who decreased (faster group) in reaction time in the incongruent Stroop task. Physiological and behavioural data analyses were performed using SPSS version 24 (IBM Corporation, Armonk, NY, USA), and differences with $p < .05$ were considered to be statistically significant.

Repeated measure analysis of variance was used to determine the effect of exhaustive exercise on reaction time. When a significant interaction effect was observed, a post-hoc Bonferroni test was used to identify significant differences between the mean values and independent t-test was used to evaluate group differences in physiological parameters during exercise and changes in psychological parameters before and after the exercise. Pearson correlation coefficient was used to determine the association between changes in reaction time in the incongruent Stroop task and VAS score.

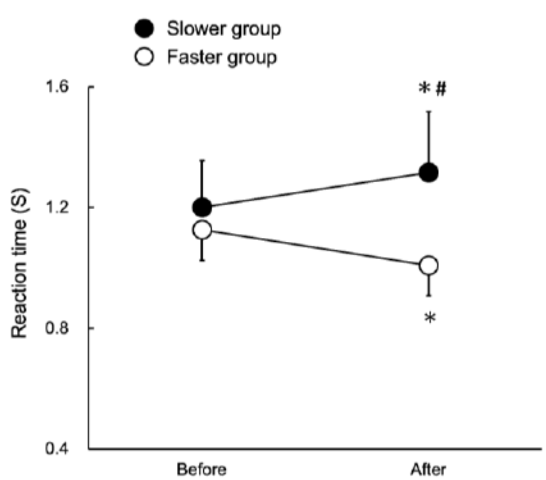
RESULTS

Six subjects exhibited an increase in reaction time, whereas 11 exhibited a decrease the reaction time; these subjects were divided into slower and faster groups. Regarding cognitive performance, the reaction time significantly decreased in the faster group after exhaustive exercise, whereas it increased in the slower group (Figure 1). The salivary cortisol and SIgA levels and VAS scores in the slower and the faster groups did not differ at baseline. The change in fatigue-VAS score was significantly different between the slower and faster groups ($p < .05$) (Table 1). There were no significant differences in time to exhaustion, peak oxygen uptake, peak heart rate, peak RPE during exercise, or changes in salivary cortisol level and SIgA flow rate and arousal- and sleepiness-VAS score between the groups. A significant correlation was observed between the increase in the fatigue-VAS score and the changes in reaction time (Figure 2; r = 0.539, $p < .05$).

Table 1. The physiological parameters during exercise, the changes in salivary cortisol level and secretary immunoglobulin A flow rate and subjective condition visual analogue scale in the slower and faster groups.

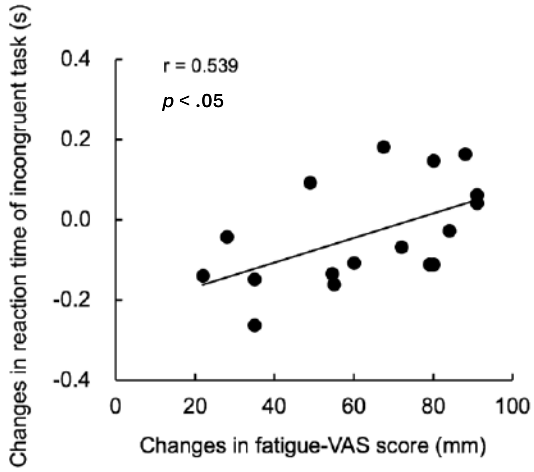
	Slower	Faster
Time to exhaustion (s)	1789 ± 168	1887 ± 438
Peak oxygen uptake (ml/min/kg)	48 ± 3	52 ± 7
Peak heart rate (bpm)	193 ± 11	186 ± 13
Peak RPE	20 ± 0.4	19 ± 1.0
Change in cortisol (μg/dL)	4 ± 14	15 ± 11
Change in SIgA (μg/min)	23 ± 177	141 ± 145
Change in fatigue-VAS (mm)	78 ± 17*	55 ± 22
Change in arousal-VAS (mm)	6 ± 29	18 ± 28
Change in sleepiness-VAS (mm)	-10 ± 40	-20 ± 22

*Note. RPE: rating of perceived exertion, SIgA: secretary immunoglobulin A. * p < .05 vs. Faster group.*



*Note. * p < .05 vs. Before, # p < .05 vs. Faster group.*

Figure 1. The reaction time before and after exhaustive exercise test in the slower and faster groups.



Note. VAS: visual analogue scale.

Figure 2. The relationship between the changes in fatigue-VAS score and reaction time in incongruent Stroop task.

DISCUSSION

This study investigated the effects of exhaustive exercise on the cognitive function using psychological and physiological parameters. The main finding was that the slower response group exhibited a greater increase in the fatigue-VAS score. The increase in the fatigue-VAS score was significantly correlated with the changes in reaction time in the incongruent Stroop task. These results suggest that the differences in cognitive functional responses to exhaustive exercise are associated with perceived fatigability.

In general, moderate-intensity aerobic exercise acutely enhances cognitive function; however, the response depends largely on exercise intensity (Cheng et al., 2012). In this regard, cognitive functions such as working memory and attention, decrease immediately after the cessation of exhaustive maximum exercise (Coco et al., 2009; Hill et al., 2019). Sudo et al. (2017) reported that reaction time in the Go/No-go test did not change significantly before and after exhaustive exercise. In contrast, Vrijikotte et al. (2018) reported that the reaction time in the Flanker test was faster after exhaustive exercise than at baseline. Collectively, the results regarding the cognitive function response to the exhaustive exercise do not reach a general consensus. In this study, the overall average cognitive function evaluated by the reaction time in the Stroop incongruent task did not change after exhaustive exercise because we observed the extent of both slower responders and faster responders. Therefore, the response of cognitive function to the exhaustive exercise may depend on some individual differences.

In this study, we focused on the differences between negative (slower) and positive (faster) responders and further measured VAS as a subjective condition and saliva stress and immune parameters as objective conditions. No differences in physiological parameters were observed during the exhaustive exercise (Table 1). On the other hand, the magnitude of changes in the fatigue-VAS score from baseline was higher in the slower group than in the faster group (Table 1). A previous study demonstrated that 2 consecutive days of high-intensity sprint interval exercise increased the rating of physical and mental fatigue sensation and decreased cognitive function evaluated by simple and choice reaction time, visuospatial working, inhibition task, and incongruent Stroop response (Costello et al., 2022). This study revealed that cognitive performance was impaired when physical and emotional fatigue was increased by heavy exercise. In the present study, there is a significantly correlated between the changes in fatigue score and cognitive function. Furthermore, we found no differences in physiological measurements during exercise, including time to exhaustion, oxygen uptake, or heart rate, which indicated that the participants performed exercises of similar intensity and workload in the slower and faster groups. Collectively, the degree of increase in the perception of fatigue after exercise may be important for cognitive performance.

To monitor homeostatic responses to exercise leading to cumulative fatigue and overtraining, many researchers have investigated not only changes in psychological measures but also responses reflected by biochemical, hormonal, and immunological parameters (Mujika, 2017). Chronic heavy training load decreases SIgA and increases cortisol levels (Saw et al., 2016). SIgA is a psychoneuroimmunological marker, and its responses vary with individual stress level(s) (Okamura et al., 2010). Furthermore, cortisol plays a role in regulating the neuropeptide and neurotransmitter systems, affecting cognitive functions including attention, perception, memory, and emotional processing (Erickson et al., 2003). Jagar et al. (2014) reported that moderate-intensity exercise increases salivary cortisol levels and shortened the reaction time in the Franker task. They also demonstrated that high cortisol responders after exercise exhibited enhanced Franker task performance, whereas improvement in the Franker task was not observed in non-responders. However, there were no differences in changes in salivary cortisol or SIgA levels between the groups, whereas perceived fatigue score was significantly higher in the slower group than in the faster group in the present study. It is possible that the cognitive function response to exhaustive function is associated with psychological fatigue rather than a physiological homeostatic response.

The present study has limitations. First, this study was conducted using a relatively small sample size and non-athlete general population. Exercise-induced fatigue would cause deterioration in cognitive function including reaction time, visual perception, and concentration in athlete, which affects athletic performance or strategic decision making in the game (Zwierko et al., 2022). Therefore, the results of the present study may limit our generalizing our findings to athletes. Another limitation is the reliance on a simple self-reported visual analogue scale to assess the psychological parameters such as perceived fatigability. Further studies are necessary to evaluate comprehensively nature of fatigue and investigate its relation to cognitive function and athletic performance.

In conclusion, using an exhaustive exercise under submaximal intensity, the present study compared cognitive function responses to exercise between slower and faster reaction time groups. Results revealed that the slower group exhibited a larger increased in fatigue-VAS scores. These results suggest that the cognitive function response to exhaustive exercise may be associated with the perception of exercise fatigability.

AUTHOR CONTRIBUTIONS

Nobuhiko Akazawa: design of the study, data analysis and interpretation, and writing the manuscript. Mana Otomo: data analysis and interpretation, and review and editing the manuscript. Mariko Nakamura: data analysis and interpretation, and review and editing the manuscript. All authors have approved the final version of the manuscript.

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No potential conflict of interest was reported by the authors.

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Effects of rapid weight loss on grip strength of national-level male judokas during simulated bout

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ABSTRACT

Rapid weight loss (RWL) is a common practice among combat sports athletes, particularly judokas, to compete within weight categories. This study examines the impact of RWL on isometric forearm strength and perceived exertion during a simulated bout among national-level male judokas. A total of 15 male judokas (age: 20.4 ± 2.0 y) participated in the study. Simulated judo bouts were conducted at three time points: baseline (before RWL), Phase 1 (72 hours after baseline, post 5% RWL), and Phase 2 (7 days after Phase 1). Handgrip strength (HGS) and rating of perceived exertion (RPE) were measured before and after bouts at each time point. Results demonstrated significant reductions in HGS post-bout across all phases (all $p <$ .001). In addition, the pre-bout HGS of the right hand in Phase 1 was significantly lower compared to Phase 2. The RPE was higher in Phase 1 compared to Phase 2. These findings suggest that RWL negatively affects the HGS of the right arm and also increases perceived exertion after simulated bouts.
Keywords: Performance analysis, Body weight changes, Weight loss, Hand strength, Muscle strength, Athletic performance, Physical exertion, Physical fitness.

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INTRODUCTION

Rapid weight loss (RWL) is a common practice in combat sports, particularly among athletes competing in weight-classified disciplines (Martínez-Rodríguez et al. 2021). This practice is often employed to achieve a competitive edge by allowing athletes to compete in lower weight categories, which can enhance their performance against opponents who may be perceived as weaker due to size differences (Lakicevic et al. 2022; Lakicevic et al. 2020; Martínez-Aranda et al. 2023; Peacock et al. 2023). Research indicates that a significant proportion of judo athletes engage in RWL, with studies showing that approximately 40% of competitors have lost more than 5% of their body mass at least once, typically through methods that include dehydration and caloric restriction (Santos et al. 2024). The implications of such practices are multifaceted, affecting not only the athletes' physical capabilities but also their psychological and physiological states during competition (Lakicevic et al. 2022; Yu et al. 2024).

The forearm strength has also been shown to be affected by RWL strategies (Isacco et al. 2020). Assessing forearm strength is critical in judo as it serves as a key performance metric. Hand grip strength (HGS) is indicative of overall muscular strength and is essential for executing various techniques in judo, such as holds and throws. Studies have demonstrated that RWL can lead to a significant decrease in hand grip strength, which may impair an athlete's performance during high-intensity bouts (Lakicevic et al. 2020). This reduction in strength can be attributed to the physiological stress imposed by RWL, which often results in decreased muscle mass and compromised neuromuscular function (Lakicevic et al. 2020; Martínez-Aranda et al. 2023). Assessing forearm HGS is critical in judo, as it serves as a key performance metric (Demiral et al. 2024). HGS is essential for executing various techniques in judo, including holds and throws. Consequently, understanding the impact of RWL on HGS is vital for evaluating the overall performance and safety of judo athletes. Therefore, understanding the impact of RWL on HGS is vital for evaluating the overall performance and safety of judo athletes (Demiral et al. 2024). The purpose of this study was to find the effects of RWL on HGS and perceived exertion among national-level judoka during simulated bouts.

METHODOLOGY

Participants

This cross-over study involved a total of 15 male national-level judo players with an age of 20.4 ± 2.0 years, body weight of 60.6 ± 5.7 kgs, and height of 164.6 ± 3.3 cm. To qualify for inclusion in the experiment, participants were required to have a minimum of five years of competitive judo experience and to have utilized RWL methods within the preceding two years. All participants were required to be free from injury at the time of testing. Before the study, the benefits, risks, and procedures involved were thoroughly explained to each participant, who voluntarily consented by signing an informed consent form. Body composition parameters were assessed using a body composition analyser (Omron BF511, Omron Healthcare Ltd., Matsusaka, Japan). All study procedures adhered to the ethical guidelines outlined in the Declaration of Helsinki and received approval from the internal review board of the Rashtriya Raksha University.

Experimental approach to the problem

HGS and the rating of perceived exertion (RPE) were measured at three distinct time points: baseline (BL; before RWL), Phase 1 (P1; after RWL [i.e., 72 hours after BL), and Phase 2 (P2; 7 days after P1), as shown in Figure 1. The BL was conducted before any weight reduction. In Phase 1, participants were required to lose 5% of their body mass within three days before undergoing a simulated fight, which took place on the 3rd day. The second measurement, P1, was taken immediately after this simulated fight. P2 measurements were conducted seven days following P1. The methods employed for weight loss included dehydration, dietary restrictions, and increased training intensity without using laxatives and diuretics, as suggested by Isacco et al. (2020). RPE was measured using the Borg CR-10 scale, which provides a subjective assessment of exertion levels experienced by the athletes during the bouts.

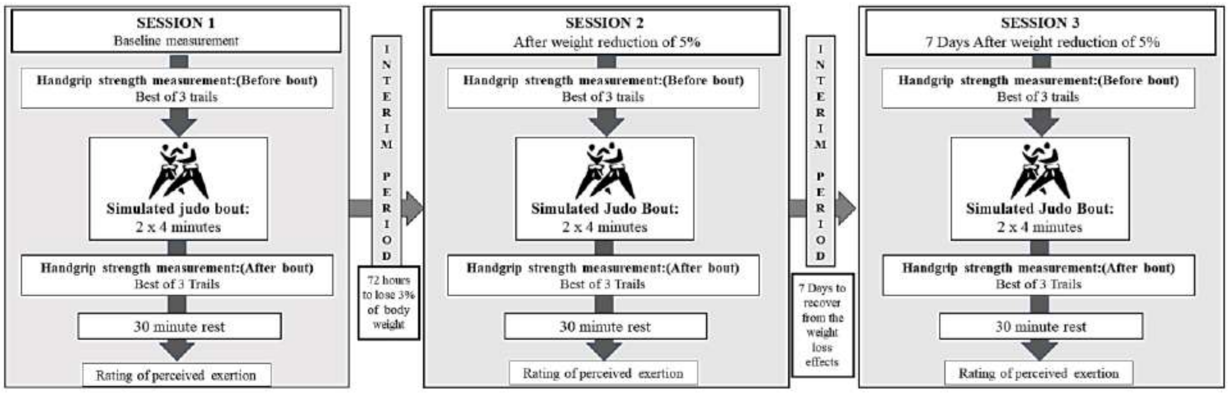

Figure 1. Graphical representation of the experimental study design: The figure illustrates the measurement timeline for handgrip strength and rating of perceived exertion at baseline (BL), phase 1 (P1), and phase 2 (P2).

The simulated judo bout

The simulated fight was designed with modifications to induce volitional exhaustion among the participants. This methodology aligns with the findings of the pilot study conducted by Del Vecchio et al. (2018), which demonstrated that varying the number of opponents in simulated judo combats influences technical-tactical actions, physiological demands, and neuromuscular responses. It consisted of two bouts lasting four minutes each, performed at full intensity to mimic a competitive situation, including a golden score period of four minutes and a regular bout scenario of four minutes. To maximize exertion, each participant faced two Uke (opponents), with each Uke engaging with the participant for a duration of four minutes. After the first four-minute bout concluded, the second Uke immediately replaced the first without any recovery interval, ensuring continuous exertion for the full eight-minute session. No winners were declared during these bouts, maintaining the focus on sustained effort and compliance with International Judo Federation (IJF) rules. Each Uke was matched to the participant based on similar weight categories to simulate realistic combat conditions.

Isometric handgrip strength

The assessment of isometric HGS was conducted using a hydraulic handgrip dynamometer (Carci®, SH 5001 model) (Venegas-Carro et al. 2022). Participants were instructed to sit comfortably in a chair, ensuring their feet were flat on the floor and their backs were supported for optimal posture. The arm was positioned at the end of the chair arm, maintaining a 90° flexion at the elbow.

Prior to the test, participants were guided to inhale through their noses and exhale through pursed lips while simultaneously flexing and squeezing their fingers around the dynamometer. Each subject performed a maximum voluntary contraction on the dynamometer for a duration of five seconds. To ensure reliability and accuracy, three trials were conducted for each hand, with the best performance from these trials selected for further analysis.

Statistical analysis

The normality of the data was verified using the Shapiro-Wilk test. Data are presented as mean and standard deviation. A two-way repeated measures analysis of variance (ANOVA) was applied to determine the main effects of bout and time on HGS, as well as the interaction effects. For the RPE data, Friedman's two-way analysis of variance by ranks was employed due to the ordinal nature of the scale. Post hoc pairwise comparisons with Bonferroni correction were conducted to identify specific differences between phases and time points. The analysis was conducted using SPSS software. For all the analyses, the level of significance was set at $p \leq .05$.

RESULT

Table 1 presents the statistical results. The post-hoc test revealed significant main effects of time on left and right HGS ($p < .001$). However, the interaction effects (time × bout) for HGS were not significant for both left and right hands ($p = .877$ and $p = .163$, respectively). Post hoc analysis demonstrated significant reductions in HGS post-bout across all phases, as well as differences between baseline and P1 and between P1 and P2.

Table 1. Statistical analysis.

Variables	Baseline		After RWL		One week after RWL	
	Pre-bout	Post-bout	Pre-bout	Post-bout	Pre-bout	Post-bout
Handgrip left (Kg)	105.7 ± 6.9	96.9 ± 11.5*	103.3 ± 10.2	95.1 ± 11.1*	105.2 ± 8.2	96.5 ± 10.9*
Handgrip right (Kg)	106.3 ± 9.5[ab]	97.9 ± 10.2*	102.1 ± 9.0[ac]	96.9 ± 11.4*	104.5 ± 9.0[bc]	98.2 ± 9.7*
RPE	7 ± 0.7		7.5 ± 1.1[c]		6.9 ± 0.7[c]	
Body mass (kg)	59.7 ± 6.4[ab]		57.4 ± 6.3[ac]		60.8 ± 6.4[bc]	

Variables	Main effect Bout (*p*-value)	Time × bout (*p*-value)
Handgrip left (Kg)	<.001	.877
Handgrip right (Kg)	<.001	.163
RPE	.008#	
Body mass (kg)	<.001	

***Note**: # - Friedman's two-way analysis of variance, * significant difference from pre-bout scores, a – significant difference between baseline and after weight loss, b – significant difference between baseline and one-week after weight loss, c – significant difference between after weight loss and one-week after weight loss, RWL – rapid weight loss.*

The result of the findings suggested that for left HGS, there was a significant reduction in post-bout scores compared to pre-bout scores across all phases (Table 1). At the baseline, the left HGS decreased from 105.7 ± 6.9 kg to 96.9 ± 11.5 kg after the bout ($p < .001$). In phase 1, the corresponding values were 103.3 ± 10.2 kg pre-bout and 95.1 ± 11.1 kg post-bout ($p < .001$). Similarly, in phase 2, the mean values decreased from 105.2 ± 8.2 kg pre-bout to 96.5 ± 10.9 kg post-bout ($p < .001$), as shown in Figure 2.

For right HGS, a significant reduction was also observed in post-bout scores compared to pre-bout scores across all phases. At the baseline, the mean right HGS decreased from 106.3 ± 9.5 kg to 97.9 ± 10.2 kg after the bout ($p < .001$). In phase 1, the values declined from 102.1 ± 9.0 kg pre-bout to 96.9 ± 11.4 kg post-bout ($p < .001$). In phase 2, the mean right HGS decreased from 104.5 ± 9.0 kg pre-bout to 98.2 ± 9.7 kg post-bout ($p < .001$). Additionally, significant differences were observed in right HGS between baseline and P1, as well as between P1 and P2, with recovery noted by the second phase.

For RPE, Friedman's two-way analysis indicated a significant difference between phases ($p = .008$). Post hoc analysis highlighted an increase in perceived exertion following weight loss (P1) compared to baseline and a reduction in perceived exertion from P1 to P2.

The RPE exhibited significant differences across phases. At baseline, the mean RPE score was 7.0 ± 0.7. Following rapid weight loss in phase 1, the RPE score increased to 7.5 ± 1.1. In phase 2, one week after weight loss, the RPE score decreased to 6.9 ± 0.7. Statistical analysis confirmed a significant difference in RPE values across phases ($p = .008$), with post hoc analysis indicating significant increases from baseline to P1 and significant decreases from P1 to P2.

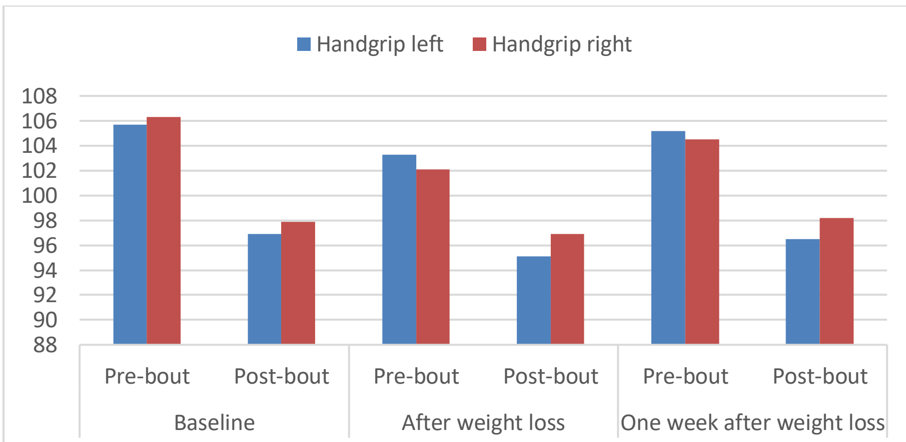

Figure 2. Changes in handgrip strength and rating of perceived exertion across phases.

DISCUSSION

The study aimed to examine the effects of RWL on isometric forearm strength and perceived exertion among national-level judoka after a simulated bout. The findings revealed significant changes in HGS after the simulated bout in all three phases. However, the pre-bout HGS of the right hand was significantly lower after RWL compared to the pre-bout HGS of baseline and one week after RWL. Higher RPE was reported by participants post bouts after RWL compared to one-week after RWL.

This reduction in HGS can be attributed to the physiological stress imposed by the RWL methods, including dehydration, caloric restriction, and increased training intensity. These methods are known to affect muscle functionality, particularly in small muscle groups such as those in the forearm, due to the depletion of glycogen stores and intracellular water content, which are critical for optimal muscle contraction (Lakicevic et al. 2020). Interestingly, HGS values partially recovered by P2, measured one-week post-weight loss. Although these values remained lower than baseline levels, the observed improvement suggests that the cessation of weight-loss practices and subsequent nutritional and hydration recovery may have contributed to the restoration of muscle function. However, the persistence of suboptimal strength levels highlights the potential long-term physiological effects of RWL, even after a short recovery period. This finding aligns with previous research suggesting that RWL can lead to prolonged impairments in performance and recovery (Brechney et al. 2022; Martínez-Aranda et al. 2023).

The RPE scores further corroborate the adverse effects of RWL on performance. Athletes reported a higher perceived exertion during bouts in P1 compared to BL and P2, emphasizing the heightened subjective difficulty of competing under conditions of weight loss-induced stress. The elevated RPE may be linked to the compounded effects of energy deficit, dehydration, and increased physical and mental strain experienced during RWL (Eston 2012; Martínez-Aranda et al. 2023). Notably, RPE scores in P2 returned closer to baseline levels, suggesting some degree of physiological adaptation or recovery. From a practical perspective, the findings of this study have important implications for judoka and their coaches. While RWL is a common practice in combat sports to meet weight-category requirements, its detrimental impact on muscle strength and perceived exertion raises concerns regarding performance and safety during competition. These results advocate for a more cautious and scientifically informed approach to weight management, prioritizing gradual weight loss strategies over rapid methods. Furthermore, the partial recovery observed in P2 underscores the need for extended recovery periods and structured rehydration and refeeding protocols post-competition to mitigate the adverse effects of RWL (Reale et al. 2017; Santos et al. 2024).

The physiological stress resulting from RWL has been documented in various studies, indicating that athletes often experience significant reductions in strength and endurance following RWL (Fortes et al. 2017; Mendes et al. 2013; Murugappan et al. 2022). This is particularly relevant in combat sports, where athletes frequently engage in weight-cutting practices to qualify for lower weight classes. The physiological mechanisms underlying these impairments includes dehydration, which can lead to reduced plasma volume and increased blood viscosity, ultimately affecting muscle performance (Mendes et al. 2013). Additionally, caloric restriction can result in decreased glycogen stores, which are essential for energy production during high-intensity exercise (McMurray et al. 1991; Ranisavljev et al. 2022). Moreover, the psychological impact of RWL cannot be overlooked. The increased RPE reported by athletes during P1 suggests that the mental strain associated with weight loss may further exacerbate feelings of fatigue and exertion during competition (Brito et al. 2012; Mendes et al. 2013). This aligns with findings from other studies that have shown a correlation between psychological stress and perceived exertion in athletes (Hanton et al. 2005; Pedersen 2000). The recovery observed in RPE scores during P2 may indicate a return to a more stable psychological state, allowing athletes to perform closer to their baseline capabilities (Brito et al. 2012).

There are a few limitations that should be acknowledged. Firstly, the samples included only male participants, and thus, the findings should not be extrapolated to females. Secondly, the participants were national-level judokas. The effects of RWL may differ between different participation levels. Thirdly, the inclusion of other variables, such as countermovement jump on force platforms before and after the bout, could provide a better understanding of the effects of RWL on lower extremity muscles.

CONCLUSION

In conclusion, this study demonstrates a significant reduction in pre-bout right HGS following RWL among national-level judokas. The findings indicate that while RWL leads to an acute decline in HGS, there are no additional effects on HGS post-bout, suggesting that the immediate impact of RWL is confined to the pre-bout phase. However, athletes reported higher RPE scores post-bout after RWL, indicating a negative effect on their perceived effort during competition.

AUTHOR CONTRIBUTIONS

Study Design: MH, RCY, and RKT; Data Collection: MH; Statistical Analysis: RKT; Data Interpretation: RKT; Manuscript Preparation: MH, RCY, and RKT wrote or revised the manuscript draft. All authors have read and agreed to the published version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY

All data generated or analysed during this study are included in the published article as Table(s) and Figure(s). Any other data requirement can be directed to the corresponding author upon reasonable request.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of School of Physical Education and Sports, Rashtriya Raksha University (protocol code IRB/SPES/2023-24/05). All participants and their legal guardian were informed about the purpose, content, and potential benefits and risk associated with the study, and the legal guardian signed the informed consent forms and participants provided their verbal assent.

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ORIGINAL ARTICLE

Rest periods effect on biophysical responses during interval training at critical swimming velocity

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ABSTRACT

This study aimed to examine the effects of rest periods on physiological and mechanical parameters during interval training (IT) using critical swimming velocity (CV). Ten male national-level competitive swimmers (19.5 ± 1.1 years old) swam 20 × 100 m (100IT) and 10 × 200 m (200IT) depend on critical velocity under different rest conditions. Rest periods for each IT were 10 seconds (R1) and 20 seconds (R2) per 100 m repetitive swimming distance. Heart rate (HR), rating of perceived exertion (RPE), blood lactate concentration, stroke rate, and stroke length (SL) were measured during all IT sets. HR significantly differed between R1 (164.0–173.0 beats per minute [bpm]) and R2 (151.7–165.1 bpm) throughout the 100IT but did not during the 200IT (160.1–173.5 and 157.3–167.8 bpm, respectively) ($p < .05$). Moreover, the mean SL during the 100IT was significantly lower in R1 than in R2 ($p < .05$). However, the HR and RPE increased significantly in both 100IT and 200IT irrespective of rest periods ($p < .05$). Therefore, all IT sets were appropriate conditions for endurance training. Rest periods may have influenced the physiological and mechanical stimulation in the 100IT at CV, suggesting that aerobic metabolism differs between conditions.
Keywords: Performance analysis, Athletes, Endurance training, Physiological cost, Heart rate, Stroke length, Training zone.

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INTRODUCTION

In competitive swimming, endurance training is categorized in terms of training intensity based on biophysical responses (Fenandes et al., 2024; Monteiro et al., 2023), and the total distance per category varies according to the swimmer's specialization (distance) (Hellard et al., 2022). Therefore, this information is useful for swimming coaches to identify the physiological and mechanical responses of endurance training sets.

Endurance training sets for competitive swimmers are mainly structured using interval training (IT), considering that the intensity of swimming sets can be easily adjusted according to the swimming velocity, repetitive swimming distance, and rest periods (Olbrecht et al., 1985; Billat, 2001). IT is also more effective than continuous training, which involves swimming at a constant pace, because it can maintain the same velocity for longer periods of time and reduce the decline in mechanical parameters (Almeida et al., 2022; Oliveira et al., 2012).

Shimoyama et al. (2003) found that the shorter the rest period, the higher the $\dot{V}O_2$ in IT in competitive swimmers. In other words, rest periods in IT may influence energy supply dynamics. Therefore, considering not only the swimming velocity and distance but also the rest periods is important to control the intensity of the swimming set in IT.

In IT, several physiological indices are employed to set swimming velocity, such as the onset of blood lactate accumulation (OBLA), maximal lactate steady state (MLSS), and anaerobic threshold (AT). However, these indices are often underutilized in swimming training due to complex procedures required, such as blood sampling and measurement of exhaled gases. The slope of swimming distance vs. time the regression line denotes the critical swimming velocity (CV) and is theoretically the maximum swimming velocity at which a swimmer can continue swimming for a long period of time without reaching exhaustion (Wakayoshi et al., 1992). CV correlates with physiological indices such as the OBLA (Wakayoshi et al., 1992; Wakayoshi et al., 1993), MLSS (Machado et al., 2011; Machado et al., 2019; Nikitakis et al., 2019), and AT (Wakayoshi et al., 1992), thereby used as a training intensity index that can be determined noninvasively.

Indeed, a study of continuous training with CV reported that the mean swimming time was 24.3 ± 7.7 min, with metabolic responses reaching maximal oxygen uptake ($\dot{V}O_{2max}$) and blood lactate concentration (BLa) being enhanced (Dekerle et al., 2010). Conversely, when IT was performed with CV, the heart rate (HR) and rating of perceived exertion (RPE) were enhanced, but the BLa remained stable. Furthermore, the intensity of the swimming set decreased as the repetitive swimming distances decreased in IT at CV (Funai et al., 2025). Thus, the influence of training style and repetitive swimming distance on physiological cost is evident in IT at CV.

However, the influence of rest periods on the physiological and mechanical parameters in IT at CV is still unverified. Clarifying the effect of rest periods on IT at CV would be a useful insight for coaches to design more effective endurance training strategies.

This study aimed to determine the effect of rest periods on physiological responses and mechanical parameters in IT using CV in national-level competitive swimmers. In this study, repetitive swimming distances of 100 and 200 m were applied for the IT, with two different rest periods in each of these IT protocols. We hypothesized that shorter rest periods have a higher physiological cost in both IT protocols. On the basis of the study results, we present practical applications of IT at CV for coaching situations.

MATERIAL AND METHODS

Participants

Ten nationally competitive male collegiate swimmers participated in the study (mean values for age: 19.5 ± 1.1 years, height: 168.0 ± 3.1 cm, body mass: 64.4 ± 4.2 kg, World Aquatics points: 738.1 ± 28.2). They specialized in middle-distance swimming (3 in 400 m freestyle, 2 in 400 m individual medley, 1 in 200 m butterfly, 3 in 200 m backstroke, and 1 in 200 m breaststroke) and had been competing for at least 8 years. All of them trained nine training sessions, which total over 45 km per week in water, as well as dryland workouts. They all provided written informed consent before participating in the experiment. None of the athletes reported any physical limitations, health problems, or injuries that would interfere with the study.

Study design

We instructed the participants to refrain from intense training for 24 h before the study, avoid any other exercise, and maintain a normal diet and sleep pattern throughout the study period.

In this experiment, we conducted four interval sessions after determining the CV in a 50 m indoor swimming pool (water temperature, 29.1°C ± 0.4°C). Participants performed front crawl swimming initiated with a push off start in all tests. Each test was preceded by a standardized warmup and a 20 min rest period. The standardized warmup (Neiva et al., 2017) included 200 m whole-body swimming (low–medium intensity), 2 × 100 m leg kick swimming (medium intensity), 4 × 50 m whole-body swimming (25 m drill/25 m low intensity), 6 × 50 m whole-body swimming (25 m race pace/25 m low intensity), and 100 m whole-body swimming (low intensity).

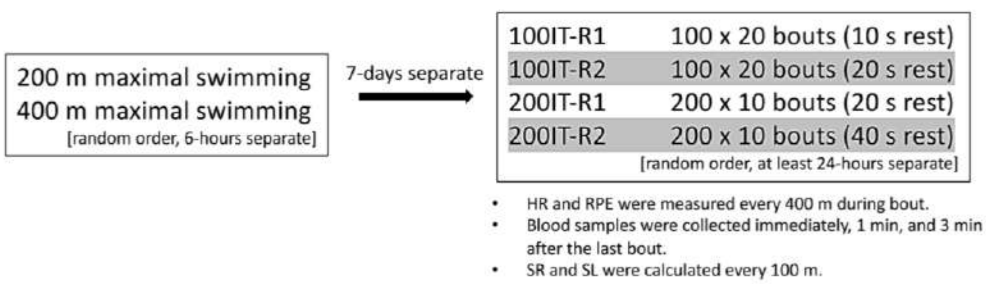


Figure 1. Experimental protocol of the study. HR: heart rate; RPE: rating of perceived exertion; SR: stroke rate; SL: stroke length.

CV determination

Swimmers performed 200 and 400 m maximal swimming bouts in a random order for CV determination, with an interval of 6 h between these two bouts (Figure 1). A linear regression between swimming distance and time was then obtained using the same method as that of Wakayoshi et al. (1993), and the slope of this line was used as the CV.

IT at CV

One week after the 200 and 400 m maximal swimming sessions, the swimmers performed 20 × 100 m (100IT) and 10 × 200 m (200IT) each under two different rest conditions. The rest periods in each IT were 10 and 20 s per 100 m of repetitive swimming distance. In other words, four tests were conducted: 10 s (100IT-R1) and 20 s (100IT-R2) for 100IT and 20 s (200IT-R1) and 40 s (200IT-R2) for 200IT in a random order based on the CV (Figure 1). These tests were performed randomly with at least 24 h apart and administered at the same time of the day (±1 hour) for each swimmer to minimize the influence of circadian fluctuations on performance. During the IT, the swimmers wore an underwater exercise-compatible Walkman (NW-WS623, Sony) to control their swimming velocity. This water-resistant neckband-type device was properly secured to the back of the head. Swimmers were instructed to pass through markers placed every 5 m at the bottom of the pool, in time with audio cues created according to their CV.

Measurements

For both the CV determination and IT, swimming times were measured by experienced coaching staff using a stopwatch (SVAS003, SEIKO, Japan). For physiological parameters during the IT, we measured HR and RPE every 400 m during the bouts. HR was measured using a wristwatch HR sensor (M600; Polar, Oulu, Finland), and RPE was determined by verbal questioning using the Japanese version of Borg's 6–20 scale (Onodera and Miyashita, 1976). BLa was measured using a portable lactate analyser (Lactate Pro 2, ARKRAY, Japan). Blood samples were extracted from fingertips immediately, 1 min, and 3 min after the last session, with the highest value recorded.

All IT sessions were filmed from land using a digital video camera (HDR-CX470 operating at 60 Hz; Sony, Japan) to calculate the stroke rate (SR) and stroke length (SL). This camera was positioned 10 m away from the swimmers at the centre of the pool, filming the swimmers vertically; then, SR and SL were analysed using video analysis software (OTL-8PZ, Octal, Japan). In all IT sessions, SR and SL were calculated every 100 m. In each 100 m, the mean stroke time was calculated from as many strokes as possible between 15 and 35 m in the first and second 50 m. The swimming velocity per 100 m was also calculated, and SR and SL were calculated using the following formula:

$$SR = 60 / \text{mean stroke time};$$

$$SL = \text{swimming velocity} \times 60 / SR.$$

The SR and SL for each 100 m were averaged, and these values were used for the statistical analysis.

Statistical analyses

A priori sample N was determined with G*Power (f = 0.50; α = 0.05; 1-β = 0.80). We present all performance, physiological, and mechanical parameters as mean ± standard deviation (mean ± SD). Data distribution normality was assessed using the Shapiro–Wilk test. We employed Student's t-tests to establish differences in BLa, mean SR, and mean SL between tests at 100IT and 200IT separately. HR and RPE during 100IT and 200IT were analysed by two-way analysis of variance of test and measurement points, and where significant main effects were found, significance was examined using the Bonferroni method for multiple comparisons. Furthermore, the effect size for t-tests and multiple comparisons was calculated using Cohen's d, with d classified as small (0.2–0.49), medium (0.5–0.79), or large (>0.8) depending on the absolute value (Cohen, 1988). A significance level of α = .05 was used. All statistical data were analysed using BellCurve (version 4.07, Social Survey Research Information Co., Ltd., Tokyo, Japan) for Excel software (Microsoft Corp., WA, USA).

RESULTS

The mean swimming times in the 200 and 400 m maximal swimming sessions were 122.83 ± 3.73 and 261.80 ± 10.25 s, respectively, and the mean calculated CV value was 1.44 ± 0.07 m/s. Table 1 shows the BLa, mean SR, and mean SL in 100IT and 200IT. BLa did not significantly differ between the conditions for 100IT

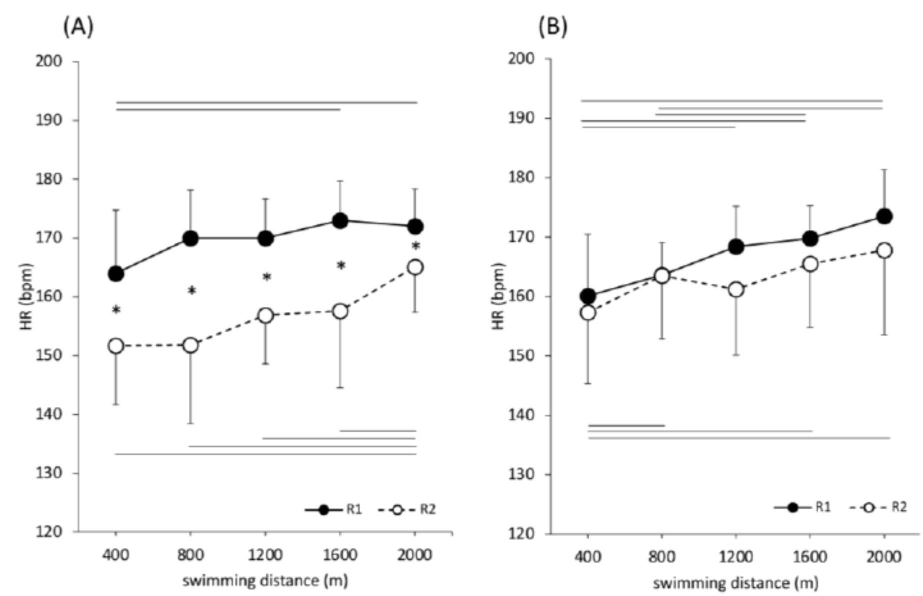
(p > .05, d = 0.03) and 200IT (p > .05, d = 0.05). However, the mean SR (p < .05, d = 0.37) and SL (p < .05, d = 0.31) significantly differed between the conditions in the 100IT alone.

Table 1. Mean ± standard deviation of blood lactate concentration (BLa), mean stroke rate (SR) and mean stroke length (SL) during the 100IT and 200IT.

		R1	R2
BLa (mmol/L)	100IT	4.12 ± 2.53	4.04 ± 2.55
	200IT	4.86 ± 2.79	5.01 ± 2.81
Mean SR (cycles/min)	100IT	41.40 ± 4.75 *	39.91 ± 3.20
	200IT	41.26 ± 3.70	41.09 ± 4.03
Mean SL (m/cycle)	100IT	2.45 ± 0.28 *	2.52 ± 0.20
	200IT	2.44 ± 0.22	2.46 ± 0.24

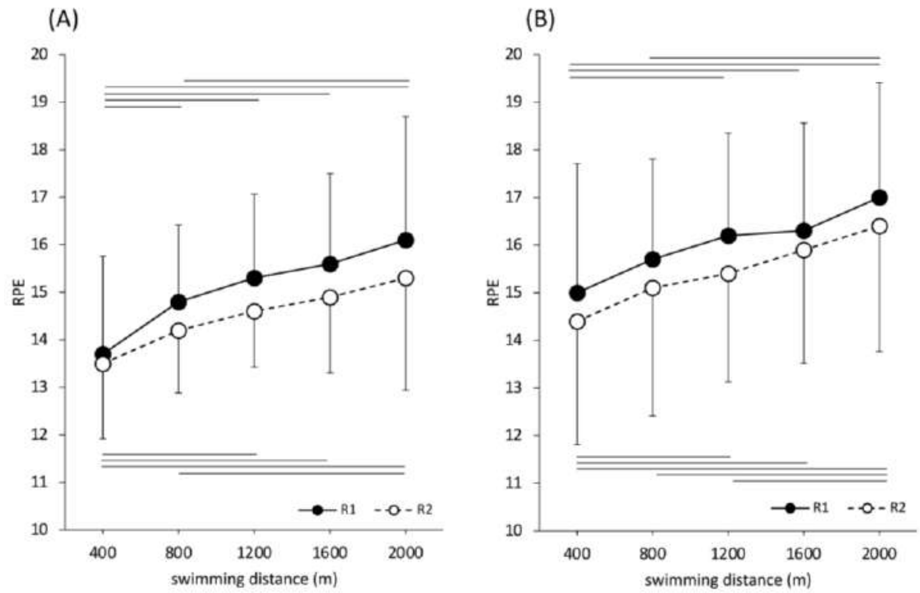
*Note. * Significant differences between R1 and R2 (p < .05). IT: interval training; R1: 10 s rest period per 100 m of repetitive swimming distance; R2: 20 s rest period per 100 m of repetitive swimming distance.*

Figures 2 and 3 show the changes in HR and RPE during 100IT and 200IT. For HR, 100IT-R1 (164.0 ± 10.6–173.0 ± 6.7 beats per minute [bpm]) was significantly higher than 100IT-R2 (151.7 ± 10. 1–165.1 ± 7.7 bpm) (p < .01, d > 0.98) at all measurement points. Conversely, HR did not significantly differ between 200IT-R1 (160.1 ± 10.4–173.5 ± 7.9 bpm) and 200IT-R2 (157.3 ± 11.9–167.8 ± 14.2 bpm) (p > .05, d < 0.51). As for RPE, no significant difference was noted between tests for both 100IT (R1: 13.7 ± 2.1–16.1 ± 2.6, R2: 13.5 ± 1.6–15.3 ± 2.4) and 200IT (R1: 15.0 ± 2.7–17.0 ± 2.4, R2: 14.4 ± 2.6–16.4 ± 2.6) in all measurement points (100IT: p > .05, d < 0.47; 200IT: p > .05, d < 0.36). In all tests, HR (100IT-R1: p < .01, d > 0.91; 100IT-R2: p < .01, d > 0.70; 200IT-R1: p < .05, d > 0.95; 200IT-R2: p < . 05, d > 0.52) and RPE (100IT-R1: p < .05, d > 0.59; 100IT-R2: p < .05, d > 0.58; 200IT-R1: p < .01, d > 0.49; 200IT-R2: p < .01, d > 0.41) significantly increased.



*Note. Data are expressed as mean ± standard deviation. The lines above and below the points indicate significant differences (p < .05); * Significant differences between R1 and R2 (p < .05). R1: 10 s rest period per 100 m of repetitive swimming distance; R2: 20 s rest period per 100 m of repetitive swimming distance.*

Figure 2. Changes in heart rate (HR) during the 20 × 100 and 10 × 200 m interval training (A and B, respectively).



Note. Data are expressed as mean ± standard deviation. The lines above and below the points indicate significant differences (p < .05). R1: 10 s rest period per 100 m of repetitive swimming distance; R2: 20 s rest period per 100 m of repetitive swimming distance.

Figure 3. Changes in the rating of perceived exertion (RPE) during the 20 × 100 and 10 × 200 m interval training (A and B, respectively).

DISCUSSION

Previous studies of IT in competitive swimming used rest periods of 10–20 s every 100 m repetitive swimming distance (Almeida et al., 2021; Shimoyama et al., 1999). However, metabolic functions reportedly differ according to small differences in rest periods (Rodriguez and Mader, 2010). Therefore, the present study examined physiological and mechanical parameters in 100IT and 200IT under two conditions of 10 s and 20 s per 100 m repetitive swimming distance. Results showed that HR and mean SR were significantly higher in 10 s rest than in 20 s rest and that mean SL was significantly shorter in 100IT than in 200IT. In addition, HR and RPE increased significantly in both 100IT and 200IT irrespective of rest periods.

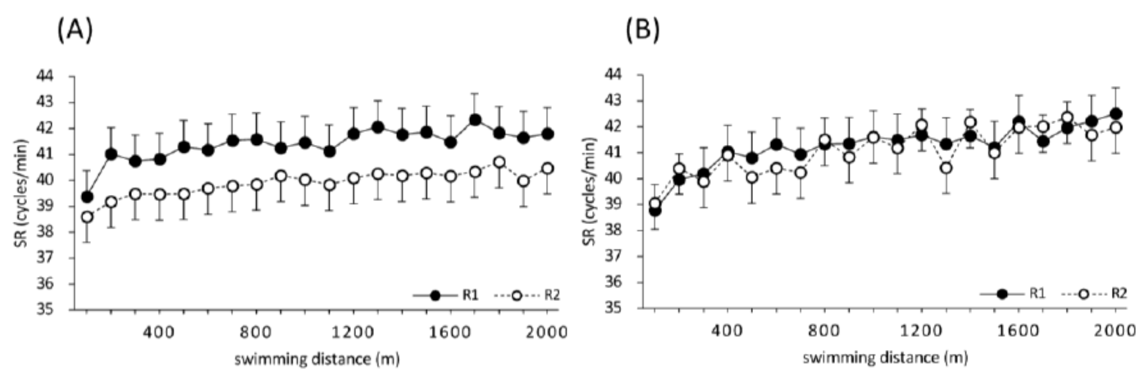
In a study measuring the metabolic response to IT and continuous training, $\dot{V}O_{2max}$ did not differ between the two training types (Almeida et al., 2022). However, the energy supply through the adenosine triphosphate–creatine phosphate (CP) system is higher during IT because creatine phosphate resynthesis is accelerated during the rest period and used as energy for the next bout (Fox et al., 1969). IT reportedly results in a lower energy supply from the glycolytic mechanism and a slower rate of lactate accumulation (Fox et al., 1969). Therefore, IT allows exercise to be sustained for longer periods at the same swimming velocity as continuous training (Demarie et al., 2000; Almeida et al., 2021).

Shimoyama et al. (2003) compared physiological responses in a test of 20 and 30 s rest periods during repeated 1 min intermittent swimming trials at OBLA swimming speed. Results showed that although BLa did not significantly differ between the two rest conditions, $\dot{V}O_2$ was significantly higher in the 20 s rest condition, while excess postexercise oxygen consumption (EPOC) was significantly higher in the 30 s rest condition. In IT, $\dot{V}O_2$ increases with a shorter rest period, possibly attributed to an increased contribution to the aerobic energy supply mechanism to compensate for inadequate CP recovery (Shimoyama et al., 2003). The increase in EPOC with prolonged rest reportedly reflects an increase in CP resynthesis (Piiper and Spiller, 1970).

Although BLa demonstrated no difference between the two rest conditions at 100IT in our study (Table 1), HR was consistently significantly higher in R1 (Figure 2). These results may support the report of Shimoyama et al. (2003). During IT, large amounts of oxygen accumulate in muscle myoglobin, even during short rest periods; consequently, oxygen depletion is minimized, thereby preserving the glycolytic pathways during exercise (Medbo et al., 1988). This phenomenon may explain the lack of difference in BLa in the present study. Additionally, $\dot{V}O_2$ may have been higher in R1 in the 100IT, and HR, a measure of the respiratory-cardiovascular system, would have shown a significant difference between the two conditions throughout the IT. A previous study reported a relationship between HR and the contribution of aerobic mechanisms in endurance training (Ribeiro et al., 2017). Hence, R1 may result in a higher oxidative metabolism training than R2 in 100IT.

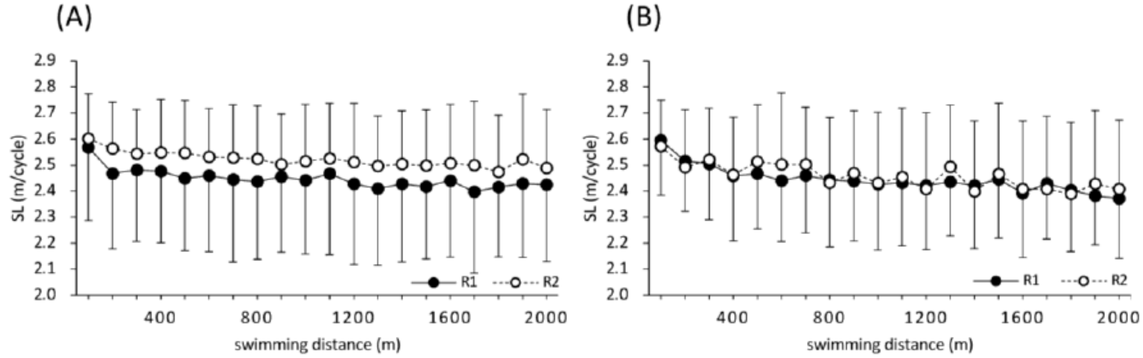
During the 200IT, HR did not significantly differ between R1 and R2. Simulations of CP recovery rates during IT by Rodriguez and Mader (2010) suggest that the majority of CP recovery occurs immediately after each bout until approximately 20 s, after which recovery proceeds slowly. The ability to recover CP in the early rest period may be a factor influencing intermittent exercise performance (Balsom et al., 1992; Blonc et al., 1998). However, this hypothesis could not be confirmed because we did not examine the CP recovery rates. Nonetheless, HR demonstrated no significant difference between the two conditions during the 200IT because the swimmers had a higher rate of CP recovery in the early part of each rest period.

Few studies have investigated the effect of rest periods in IT on mechanical parameters. In the present study, the mean SR and SL differed significantly between the conditions in 100IT (Table 1). SR (Figure 4) and SL (Figure 5) per 100 m also consistently differed between the conditions in 100IT. In progressive velocity tests of swimming, mechanical parameters rapidly change at metabolic threshold levels (Oliveira et al., 2012; Figueiredo et al., 2013). When swimming at a constant swimming velocity, an increase in SR and a decrease in SL occur as the respiratory and cardiovascular parameters increase (Pelarigo et al., 2016). Thus, physiological and mechanical parameters are closely related, and the differences in SR and SL in the present study may have been collateral evidence of differences in HR between conditions at 100IT.



Note. Data are expressed as mean ± standard deviation. R1: 10 s rest period per 100 m of repetitive swimming distance; R2: 20 s rest period per 100 m of repetitive swimming distance.

Figure 4. Changes in the stroke rate (SR) during the 20 × 100 and 10 × 200 m interval training (A and B, respectively).



Note. Data are expressed as mean ± standard deviation. R1: 10 s rest period per 100 m of repetitive swimming distance; R2: 20 s rest period per 100 m of repetitive swimming distance.

Figure 5. Changes in stroke length (SL) during the 20 × 100 and 10 × 200 m interval training (A and B, respectively).

Previous studies have investigated the training zone of CV. In one study using CV, continuous swimming training lasted only 24.3 min (Dekerle et al., 2010), given that BLa, HR, and RPE continued to increase and the metabolic responses reached $\dot{V}O_{2max}$. Training that induces these physiological responses is included in the severe-intensity domain. Moreover, the physiological cost of using CV for IT is lower than that for continuous training (Dekerle et al., 2010). Previous studies using CV for 100, 200, and 400 m IT sessions reported continuous increases in HR and RPE yet a steady state in BLa (Dekerle et al., 2010; Nikitakis et al., 2019; Rizatto et al., 2018). In other words, IT in CV belongs to the heavy-intensity domain. However, training zones that consider rest periods in IT using CV have not yet been validated.

In the present study, $\dot{V}O_2$ was not measured, and BLa was only measured at the end of the test, making the training zone difficult to determine. Not only HR but also RPE significantly increased in all conditions, occurring in both heavy- and moderate-intensity domains (Fernandes et al., 2024). However, the HR at 100IT was significantly lower in R2 than in R1. According to Fernandes et al. (2024), HR-based guidelines suggest that 160–170 bpm belongs to the heavy-intensity domain and 150–160 bpm to the moderate-intensity domain. Calvalho et al. (2020) and Monteiro et al. (2023) reported differences in SR and SL between the heavy- and moderate-intensity domains, suggesting that mechanical parameters can help identify boundaries between domains. On the basis of these findings, 200IT-R1, 200IT-R2, and 100IT-R1 corresponded to the heavy-intensity domain and 100IT-R2 to the moderate-intensity domain.

The heavy-intensity domain is an intensity at or near the metabolic threshold, where mechanical parameters collapse (Calvalho et al., 2020). At this intensity, fast paces can be maintained for prolonged periods of time without causing excessive fatigue, effectively improving the associated physiological parameters (Sperlich et al., 2023). The moderate-intensity domain was below the metabolic threshold. Sessions of this intensity make up a large proportion of the endurance training in competitive swimmers (Sperlich et al., 2023), with the aim of increasing the ability to oxidize pyruvate, lactate, and lipids throughout the body and improving basic endurance (Fernandes et al. 2024). Therefore, the IT protocols in this study are effective as endurance performance–enhancing training.

According to the results of the physiological and mechanical parameters in this study, practical applications can be suggested. Specifically, 200IT-R1, 200IT-R2, and 100IT-R1 can be used as training protocols, with BLa at 4–5 mmol/L and HR at approximately 160–170 bpm. Given that the physiological cost is close to the metabolic threshold, it can be used as intermittent race pace training for long-distance swimmers, especially during the strengthening phase. Moreover, 100IT-R2 can be used for training, with BLa at approximately 4 mmol/L and HR at 150–160 bpm. This IT provides a moderate load on the respiratory and cardiovascular systems and facilitates the maintenance of the swimming technique; hence, it can be used for training, especially in the early season and for improving basic endurance.

A limitation of this study is that the rest periods used in the IT are considered to be relatively short for regional-level, junior, and masters swimmers, indicating that the results can only be applied to national-level swimmers. Second, although our method of CV determination is traditional and simple, the possibility of a higher estimate of CV cannot be ruled out. For example, CV determined in 200 and 400 m maximal swimming bouts is higher than that determined in 200, 400, and 800 m maximal swimming bouts (Petrigna et al., 2022). Therefore, the results of this study can only be applied to CV calculated in this way. Conducting more research on IT using CV in the future is necessary.

CONCLUSION

The physiological and mechanical stimuli of R1 were higher than those of R2 in 100IT. In 200IT, the effect of rest periods on these stimuli did not need to be considered. All IT sessions showed increases in HR and RPE throughout, suggesting that they are appropriate training conditions for endurance performance. In particular, the 100IT-R1, 200IT-R1, and 200IT-R2 could be effectively used for race pace training protocols close to metabolic threshold levels, while the 100IT-R2 could have a positive effect on the increasing oxidative capacity of each energy source and improving basic endurance performance.

AUTHOR CONTRIBUTIONS

Conceptualization and design: Yuki Funai and Masaru Matsunami. Data Collection: Shoichiro Taba, Yuta Kanegawa, and Yuki Funai. Formal Analysis: Shoichiro Taba, Yuta Kanegawa, and Yuki Funai. Writing (original draft): Yuki Funai. Writing (review and editing): Masaru Matsunami, Shoichiro Taba, and Yuta Kanegawa.

SUPPORTING AGENCIES

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL APPROVAL

The study was conducted in accordance with the aims of the Declaration of Helsinki and was approved by the Ethics Committee on Research Involving Human Subjects of Kumamoto Gakuen University (approved December 3, 2021).

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Home advantage in women's football: Comparison of Europe and America

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ABSTRACT

This study aims to investigate the home advantage in women's football leagues. Additionally, the difference between Europe and America was examined. The sample of the study is first-tier women's football leagues of England, Germany, Spain, France, and the United States. Variables of the study are stadium attendance (crowd support), goals scored and conceded (secondary performance outcomes), and number of wins, draws, and losses (tertiary performance outcomes). Related data were obtained from Two Circles, Soccer Stadium Digest, and Sports Reference. The analyses used in the study are Spearman's correlation analysis, the GLM mediation model, the Mann-Whitney U test, and the GLM moderated mediation test. The findings showed a significant relationship of stadium attendance with goals conceded, the number of wins, and the number of losses. Moreover, the number of goals conceded has a full mediation role in the effect of stadium attendance on the number of losses. In terms of regional differences; stadium attendance and the number of goals conceded are differentiated significantly. Lastly, the moderated mediation model was supported which means there was a strong mediation for Europe and no mediation for America. Consequently, this study supports the game location framework and a framework for home advantage in women's sports.

Keywords: Performance analysis, Home advantage, Women's football, Crowd support, Stadium attendance.

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INTRODUCTION

Home advantage is one of the most intriguing topics in football. However, it has been commonly studied in men's football (e.g. Bhagwandeen et al., 2024; Chacón-Fernández et al., 2025; Leite et al., 2023; Lyhagen, 2025). The market size and popularity of men's football can rationalize this attention. On the other hand, the market size of women's football has also been increasing. According to Deloitte (2024), one of the most prestigious global audit firms, the total revenue of Women's Super League clubs is expected to reach £68 million in 2025 which means 360% growth compared to 2020.

In addition to the increase in market size, stadium attendance one of the most influential factors of home advantage (Schwartz and Barsky, 1977), has also been rising in women's football (Statista, 2024). In spite of that, the number of studies in the literature that investigated the effect of home advantage in women's football is scarce. In this context, studies focused on comparing women's football leagues with men's (e.g. Leite and Diniz da Silva 2023; Pollard and Gomez, 2014), investigating the effect of COVID-19 on home advantage (e.g. Krumer and Smith, 2022), and testing the difference of league level (e.g. Leite and Pollard, 2020). Results showed that home advantage is less for women's football leagues than men's but still significant; 2nd tier of women's league had higher home advantage (55.5%) than 1st tier; ghost matches emerged due to the COVID-19 did not lead to a disadvantage for home teams in Scandinavian women's football league.

There is a novel framework of home advantage in women's sports in the literature developed by Leite (2023) that provides a theoretical basis for empirical studies. Within this scope, there are several factors that impact the home advantage in women's sports as psychological factors, travel effects, referee bias, socio-cultural factors, familiarity, physiological factors, tactical factors, and others. One of them is also crowd support that provides motivation for home players and pressure on away teams and referees.

Based on the statistics, literature review, and theoretical background above-mentioned; crowd support, the reflection of boosting and social support that the home team gets from its fandom (Courneya and Carron, 1992), can be labelled as a crucial element of home advantage. However, the literature includes limited studies regarding crowd support in women's football leagues. Therefore, the research question of this study is "*What is the effect of crowd support in women's football?*"

MATERIAL AND METHODS

Participants

The sample of the study includes the Women's Super League (England), Frauen-Bundesliga (Germany), Liga F (Spain), Arkema Prémiere Ligue (France), and National Women's Soccer League (United States). The most valuable women's football leagues were recruited in this study. In accordance with the purpose of the study, five leagues were categorized as European (England, Germany, Spain, France) and American (US). Therefore, only one season was considered for each European league and four seasons were considered for the American league to balance the number of observations. Additionally, reliable data for the stadium attendance in European leagues for the previous seasons could not provide. Hence, the total sample is 100 (Europe = 52, America = 48). The sample of the study is presented in Table 1 below.

Measures

The variables of the study are crowd support, secondary performance outcome, and tertiary performance outcome. In this context, measures are average stadium attendance (crowd support), goals scored and goals conceded (secondary performance outcomes), and number of wins, draws, and losses (tertiary performance outcomes).

Table 1. Sample of the study.

	League	Country	Number of Clubs	Season
Europe	Women's Super League	England	12	2023-2024
	Frauen-Bundesliga	Germany	12	2023-2024
	Liga F	Spain	16	2023-2024
	Arkema Prémiere Ligue	France	12	2023-2024
America	National Women's Soccer League	United States	14	2024
	National Women's Soccer League	United States	12	2023
	National Women's Soccer League	United States	12	2022
	National Women's Soccer League	United States	10	2021

Procedures

The data were entered on the Jamovi Version 2.2 (2021). For this purpose; region, season, league, team, stadium attendance, number of wins, draws, losses, goals scored, and conceded were obtained from Two Circles, Soccer Stadium Digest, and Sports Reference (twocircles.com; soccerstadiumdigest.com; fbref.com). The hypotheses generated according to the game location framework (Courneya and Carron, 1992) and framework for home advantage in women's sports (Leite, 2023) are given below:

H_1: Crowd support has significant relationships with secondary performance outcomes.

- H_{1a}: Stadium attendance has a significant relationship with the number of goals scored.
- H_{1b}: Stadium attendance has a significant relationship with the number of goals conceded.

H_2: Crowd support has significant relationships with tertiary performance outcomes.

- H_{2a}: Stadium attendance has a significant relationship with the number of wins.
- H_{2b}: Stadium attendance has a significant relationship with the number of draws.
- H_{2c}: Stadium attendance has a significant relationship with the number of losses.

H_3: Secondary performance outcomes mediate the effect of crowd support on tertiary performance outcomes.

- H_{3a}: The number of goals scored mediates the effect of stadium attendance on the number of wins.
- H_{3b}: The number of goals conceded mediates the effect of stadium attendance on the number of losses.

H_4: Home advantage differentiates significantly between the regions (Europe/America).

- H_{4a}: Stadium attendance differentiates significantly between the regions.
- H_{4b}: The number of goals conceded differentiates significantly between the regions.
- H_{4c}: The number of goals scored differentiates significantly between the regions.
- H_{4d}: The number of wins differentiates significantly between the regions.
- H_{4e}: The number of draws differentiates significantly between the regions.
- H_{4f}: The number of losses differentiates significantly between the regions.

H_5: The mediation role of the secondary performance outcomes is moderated by the regions.

- H_{5a}: The mediation role of the number of goals scored is moderated by the regions.
- H_{5b}: The mediation role of the number of goals conceded is moderated by the regions.

Analysis

The analysis of the study was performed on Jamovi. First, the Shapiro-Wilk test was performed to test the normality of the variables. Second, Spearman's correlation analysis was performed to test the relationship among variables. Third, the GLM mediation model (Gallucci, 2020) was performed to test the mediation role. Fourth, the Mann-Whitney U test was performed to test the differentiation of the variables according to the categorical factor. Lastly, the GLM moderated mediation test was performed to test categorical differences.

RESULTS

Normality of the variables

The findings of the Shapiro-Wilk Test are presented in Table 2 below. The number of observations is 100. Mean values are 6003 (stadium attendance), 19.3 (goals scored), 16.3 (goals conceded), 5.24 (number of wins), 2.55 (number of draws), and 4.27 (number of losses). Shapiro Wilk p values are significant for all variables which means that the data is distributed non-normally.

Table 2. Normality of the variables.

Variable	*n*	*M*	*SD*	*Shapiro-Wilk W*	*Shapiro-Wilk p*
Stadium attendance	100	6003	5720	0.823	< .001
Goals scored	100	19.3	10.3	0.790	< .001
Goals conceded	100	16.3	6.99	0.973	.036
Wins	100	5.24	2.92	0.962	.006
Draws	100	2.55	1.50	0.944	< .001
Losses	100	4.27	2.55	0.956	.002

Correlation analysis

Spearman's correlation analysis was performed among non-parametric tests due to the non-normal distribution of the data. The Spearman's rho values are significant for the relationship of stadium attendance between goals conceded, number of wins, and number of losses. The relationship of stadium attendance with goals conceded is negative and strong; with number of wins is positive and moderate, and with number of losses is negative and strong. Hence, H_{1b}, H_{2a}, and H_{2c} are supported. The correlation table for the variables is presented in Table 3 below.

Table 3. Correlation analysis result.

Variable	*n*	*1*	*2*	*3*	*4*	*5*	*6*
Stadium attendance	100	-	0.031	-0.456**	0.204*	-0.121	-0.274**
Goals scored	100	0.031	-	-0.399**	0.819**	-0.304**	-0.614**
Goals conceded	100	-0.456**	-0.399**	-	-0.667**	0.050	0.834**
Wins	100	0.204*	0.819**	-0.667**	-	-0.412**	-0.751**
Draws	100	-0.121	-0.304**	0.050	-0.412**	-	-0.046
Losses	100	-0.274**	-0.614**	0.834**	-0.751**	-0.046	-

*Note. *: p < .05, **: p < .01.*

Mediation analysis

The findings of the GLM mediation model are presented in Table 4 below. The indirect effect (mediation path) is significant (p < .001, β = -0.293) and the confidence interval does not cover zero. Component paths are both significant and show that higher stadium attendance decreases the number of goals conceded (p < .001, β = -0.342) and more goals conceded increase the number of losses (p < .001, β = 0.856). The direct effect is not significant showing that stadium attendance does not have an influence on the number of losses directly. The total effect is significant ($p < .05$, $\beta = -0.206$) showing that higher stadium attendance is related to fewer losses. Consequently, the number of goals conceded has a full mediation role in the effect of stadium attendance on the number of losses. Hence, H_{3b} is supported.

Table 4. GLM mediation model.

Type	Effect	Estimate	%95 CI		β	p
			LL	*UL*		
Indirect	Attendance⇒Goals conceded⇒Losses	-1.31e-4	-2.04e-4	-5.83e-5	-0.293	<.001
Component	Attendance⇒Goals conceded	-4.19e-4	-6.44e-4	-1.93e-4	-0.342	<.001
	Goals conceded⇒Losses	0.313	0.270	0.355	0.856	<.001
Direct	Attendance⇒Losses	3.88e-5	-1.31e-5	9.07e-5	0.087	.14
Total	Attendance⇒Losses	-9.21e-5	-1.78e-4	-6.06e-6	-0.206	.03

Note. CI = confidence interval, LL = lower limit, UL = upper limit. Confidence intervals computed with method: Standard (Delta method). Betas are completely standardized effect sizes.

Comparison of the regions

Mann-Whitney U test was performed for independent groups among non-parametric tests due to the non-normal distribution of the data. The findings of the Mann-Whitney U test are presented in Table 5 below. Within this scope, stadium attendance and the number of goals conceded are differentiated significantly. Hence, H_{4a} and H_{4c} are supported.

Table 5. Independent samples t-test.

Variable	Test	Statistic	*p*
Stadium attendance	Mann-Whitney U	245	< .05
Goals scored	Mann-Whitney U	983	.07
Goals conceded	Mann-Whitney U	741	< .05
Wins	Mann-Whitney U	1215	.82
Draws	Mann-Whitney U	1009	.09
Losses	Mann-Whitney U	1042	.15

Table 6. Group descriptives.

Variable	Group	n	M	SD
Stadium attendance	Europe	52	3095	4483
	America	48	91152	5256
Goals scored	Europe	52	21.58	12.67
	America	48	16.88	6.19
Goals conceded	Europe	52	18.77	8.09
	America	48	13.69	4.27
Wins	Europe	52	5.31	3.50
	America	48	5.17	2.17
Draws	Europe	52	2.33	1.50
	America	48	2.79	1.47
Losses	Europe	52	4.67	2.83
	America	48	3.83	2.16

Group descriptives were checked to interpret the differences among the regions. In this context, clubs from America had much more stadium attendance (*M* = 91152) than European clubs (*M* = 3095). In addition to the stadium attendance, American clubs conceded fewer goals (*M* = 13.69) than European clubs (*M* = 18.77).

GLM moderated mediation test was used to check the effect of the region. The findings are presented in Table 7 below. The indirect effect is significant for Europe ($p < .001$, β = -0.477) while it is insignificant for America ($p < .68$, β = 0.054). Additionally, the component effects mean that the effect of stadium attendance on the number of goals conceded ($p < .001$, β = -0.541). and the effect of the number of goals conceded on the number of losses ($p < .001$, β = 0.881) are both significant. Lastly, the direct effect of stadium attendance on number of losses is not significant ($p < .065$, β = 0.047). This confirms the full mediation role of the number of goals conceded in the model. On the other hand, the mediation model is not significant for America. Hence, the moderated mediation model was supported which means there was a strong mediation for Europe and no mediation for America. Eventually, higher stadium attendance provides fewer goals conceded which leads to fewer losses in Europe. This process is not valid for America because stadium attendance does not have a significant effect on goals conceded or losses. Thus, H_{5b} is supported.

Table 7. Moderated mediation analysis.

Type	Effect	Estimate	%95 CI		β	p
			LL	*UL*		
Europe						
Indirect	Attendance⇒Goals conceded⇒Losses	-2.07e−4	-3.28e−4	-8.64e−5	-0.477	<.001
Component	Attendance⇒Goals conceded	-6.62e−4	-0.001	-2.87e−4	-0.541	<.001
	Goals conceded⇒Losses	0.313	0.270	0.357	0.881	<.001
Direct	Attendance⇒Losses	2.03e-5	-6.84e−5	1.09e-4	0.047	.65
Total	Attendance⇒Losses	-1.87e−4	-3.37e−4	-3.73e−5	-0.419	.01
America						
Indirect	Attendance⇒Goals conceded⇒Losses	2.64e-5	-9.93e−5	1.52e-4	0.054	.68
Component	Attendance⇒Goals conceded	6.99e-5	-2.63e−4	4.03e-4	0.057	.68
	Goals conceded⇒Losses	0.378	0.334	0.422	0.937	<.001
Direct	Attendance⇒Losses	-1.08e−5	-8.53e−5	6.36e-5	-0.022	.78
Total	Attendance⇒Losses	1.56e-5	-1.17e−4	1.49e-4	0.035	.82

Note. Confidence intervals computed with method: Standard (Delta method). Betas are completely standardized effect sizes.

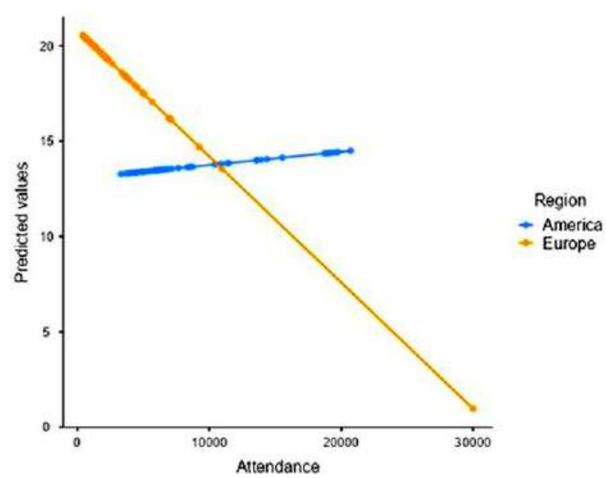

Figure 1. The scatterplot of the moderated mediation effect.

The scatterplot was used to visualize these findings (Soetaert, 2019). For this purpose, predicted values were generated to represent a moderated mediation model. In this context, predicted values were calculated via linear regression which includes the interaction term as well (attendance*region). Then the scatterplot was generated in Figure 1.

DISCUSSION

This study supports the game location framework of Courneya and Carron (1992) and a framework for home advantage in the women's sport of Leite (2023). In this respect, the crowd is a key factor for home games in women's football leagues. Additionally, the working principle of this factor in women's football was elucidated in this study. In other words, home advantage in terms of crowd provides conceding fewer goals and in turn probability of loss decreases. Therefore, it is recommended for home teams to focus on defensive strategies intensively and try to have clean sheets in home games.

In addition to the frameworks, this study also promotes some theories based on personality and gender differences. In this context, the Big Five Personality Traits developed by McGrae and Costa (1987) were examined in terms of gender differences. It was revealed that women have higher agreeableness and neuroticism, on the other hand, men have higher assertiveness (Costa et al., 2001). In this respect, the current study shows home advantage in women's football is related to goals conceded rather than goals scored. However, home advantage in men's football is more related to goal scoring (e.g. Güngör, 2025). This supports the personality differences between the genders which means the current study is parallel with the Theory of Big Five Personality Traits.

Together with the Theory of Big Five Personality Traits, Evolutionary Personality Psychology developed by Buss (1991) also claims personality differences between men and women such as women being less aggressive than men. Moreover, hormonal differences can be considered as an influential factor. Within this scope, testosterone released less in women is related to aggression, dominance, and risk-taking (e.g. Giammanco et al., 2005; Mazur and Booth, 1998; Stanton et al., 2011). This is also congruent with the current study.

From the point of regional difference, the national culture theory of Hofstede (1984, 1991) can be revealed. When Europe (England, Germany, Spain, and France) is compared with America (United States). There are noteworthy differences in the dimensions of uncertainty avoidance (Europe: 68, US: 46) and indulgence (Europe: 50, US: 68) (The Culture Factor). In this context, the US has lower uncertainty avoidance means higher openness to new experiences, freedom of expression, and lower emotional manifestation. On the other hand, the US has higher indulgence means weaker control of desires and impulses. Consequently, these traits can be a clue for the lower level of impaction for away teams in terms of crowd support.

This study has a coherence with some studies (e.g. Errico et al., 2024; Leite and Diniz da Silva 2023) in the literature as well. Accordingly, Errico and colleagues (2024) demonstrated the effect of home advantage in major women's football leagues. As distinct from the current study, they approached the crowd support as density rather than size. However, both studies confirmed the existence of home advantage via crowd. This supports the framework of Courneya and Carron (1992) that crowds can be investigated in terms of density or size. Leite and Diniz da Silva (2023) put forward the effect of socio-cultural factors on the home advantage gender gap (HAGG). Within this scope; cultural globalization, gender equality, and regional division as socio-cultural factors were explanatory roles of HAGG. This is also supportive of the current study.

Despite the theoretical contributions, this study has various limitations. From the point of regions, only five countries were included in the sample. In terms of time, the study is limited to the 2023-2024 seasons for the European Leagues. Additionally, America was just represented by the U.S. and five different seasons had to be used to balance the number of observations. The reason for these limitations is the scarce reliable statistics for stadium attendance in women's football leagues. Otherwise, the data would be enlarged. Another limitation of the study is the selection of football as the sports field.

Several suggestions can be made for future studies. For instance, apart from major women's football leagues, other leagues such as Italian, Dutch, or Portuguese can be involved. Other continents can also be incorporated in future studies such as Australia or Africa. Different kinds of sports can be compared in terms of home advantage. Other factors of home advantage as travel effect, familiarity, and referee bias, can be also investigated in women's football. Lastly, similar kinds of studies can be conducted for international teams.

CONCLUSIONS

This study investigated the home advantage in women's football leagues. For this purpose, crowd support was considered as one of the main home advantage factors. First, the relationship between crowd support and the performance outcomes of clubs was examined. The analysis demonstrated that stadium attendance significantly correlated with the number of goals conceded, wins, and losses. Then, the mediator role of goals conceded was confirmed for the effect of stadium attendance on the number of losses.

Regional differences (Europe/America) were also examined in the study. In this context, stadium attendance was higher for American women's football leagues and the number of goals conceded was less compared to the European women's football leagues. Additionally, the mediator role of the number of goals conceded was also compared according to the regions which meant the moderated-mediation role. Within this scope, this role was valid for European women's football leagues and invalid for Americans.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

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ORIGINAL ARTICLE

Game-related statistics and performance trends in the FIBA Under-17 Basketball World Cup

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ABSTRACT

The FIBA Under-17 Basketball World Cup showcases elite youth talent and shapes international basketball's future. This study identified game-related performance indicators differentiating winning from losing teams in different (Group, Second, and Final) rounds of the Under-17 Men World Cup. Data from 122 games across two consecutive Under-17 Men World Cups (Malaga 2022, Istanbul 2024) were analysed, classifying matches as closed, balanced, or unbalanced based on final score differences. Descriptive statistics quantified performance differences, while linear discriminant analysis identified key predictors of game outcomes. In the group stage, first-quarter scoring consistently predicted victory across all game types. Closed games were primarily influenced by three-point field goals made and assists, while balanced games were determined by defensive rebounds and turnovers. Second-round analysis revealed different predictors: points from turnovers in closed games, bench scoring in balanced games, and points from the paint in unbalanced games. The final round showed that points scored in the first and fourth quarters, alongside fast-break points, were consistent predictors regardless of game classification. These findings provide valuable insights for coaches developing tournament preparation strategies. Understanding how different performance indicators influence game outcomes across tournament rounds, enables tactical adjustments that maximize success probability in international youth basketball competitions.
Keywords: Performance analysis, Under-17 basketball, Discriminant analysis, Tournament trends, Performance indicators, Sport analysis.

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INTRODUCTION

The Under 17 basketball World Cup is one of the most prestigious international tournaments that bring together the most promising young players around the globe. This tournament not only serves as a platform for these players to showcase their skills and potential but also provides valuable insights into the factors that contribute to success at the youth level (Nughes et al., 2020). This tournament features national teams composed of players aged 16 and younger, allowing for the identification and development of the next generation of basketball stars (Derri et al., 1998). Game-related statistics serve multiple analytical purposes in basketball, including the evaluation of teams as well as individual players (Gasperi et al., 2020; Sampaio et al., 2006). These statistics are utilized in different contexts: during tournaments (Stavropoulos et al., 2021a) throughout the seasons (Giovanini et al., 2021), and in comparison between playoff and non-playoff teams (Akinci, 2023). Furthermore, (Ibáñez et al., 2018; Madarame, 2018a) facilitate comparative studies of the performances of teams cutting across different genders and continents.

A study by (Lorenzo et al., 2010) on junior basketball players under the age of sixteen found that assists and turnovers are important variables in close games, while defensive rebounds and successful two-point field goals are important in balanced games. In unbalanced games, successful two-point field goals are the main differentiators between winning and losing teams. Similarly, (Karasek & Mikić, 2024) compared under 17 matches of men and women of Triglav Cadet League of Serbia, and found that in close games, successful two-point field goals, defensive rebounds, and assists were the predictors in both sexes and offensive rebounds were the discriminant factors between winning and losing men's teams, whereas in balanced games, successful 2-point field goals for women's teams and assists for both sexes were discriminating factors. In unbalanced games assists for both sexes, defensive rebounds for men's teams, and successful 2-point field goals for women's teams were discriminating factors. Similarly, (Abd El-Hamid Belal, 2014) identified player height, defensive rebounds, efficiency percentage, free throws made, field goals made and attempted, effective field goal percentage, and two-point attempts as crucial factors in distinguishing winning from losing teams during the Under-17 World Cup 2012. (Madarame, 2018a) found that successful free throws rather than assists defined winners and losers in under 17 balanced games. In addition (Sampaio et al., 2004) compared junior teams with senior teams and found that the junior teams differ from senior teams by their lower percentage of assists and higher percentage of turnovers. (Madarame, 2018b) analysed Under-18 Continental Championships and pointed out different playing patterns across different regions. The African Championship was characterized by a high number of free throws. In the European Championship, teams displayed high numbers of both ball possessions and assists. The Asian Championship featured a high number of ball possessions but a lower number of assists. The American Championship showed high numbers in both possessions and assists from the findings, the author concluded that youth basketball games are played differently across various regions of the world.

At present, the number of studies focusing on the highly competitive Under-17 Basketball World Cup is sparse. Basketball is a game that is continuously evolving in the form of changes in the pace of the game, modification of rules, and players trying new skills. This rapid evolution of the game demands the reassessment of the key performance indicators in multiple phases of the tournaments (Stavropoulos et al., 2021a). This study mainly focused on finding the discriminant factors associated with winning and losing teams across the three stages of the World Cup: the group stage, second round, and final round. A total of 21 key performance indicators were analysed, with some newly introduced variables, such as points scored in the 1st, 2nd, 3rd, and 4th quarters, points from turnovers, fast breaks, second chances, paint, and bench contributions. To the best of the researcher’s knowledge, no prior studies have examined discriminants between winning and losing teams in the Under-17 category across different tournament stages. The findings from this study will provide valuable insights for coaches and players regarding current trends in basketball, enabling them to evaluate team performance and make strategies during the game. The primary objective of this paper is to identify the predictors influencing winning teams, progression to subsequent rounds, and competing for medals in the Malaga 2022 and Istanbul 2024, Men Under-17 Basketball World Cup.

MATERIALS AND METHOD

Sample and variables

This study analysed a total of 112 games from the Men Under-17 World Cup held between Malanga 2022 (n = 56) and Istanbul 2024 (n = 56), involving 16 teams in each tournament. Data was selected from the public available data from the official box scores of the FIBA Basketball website: https://www.fiba.basketball/en/events/fiba-u17-basketball-world-cup-2024/teams. The key performance indicators used in this research include: first-quarter score (1Q), second-quarter score (2Q), third-quarter score (3Q), fourth-quarter score (4Q), wo-point try (2PTry), two-point shots made (2PMade), three-point try (3P Try), three-point shots made (3PMade), free throw try (FTT), free throws made (FTM), offensive rebounds (OFR), defensive rebounds (DFR), total rebounds (RBO), assists (AST), personal fouls (PF), turnovers (TRN), steals (STL), blocks (BLK), points from turnovers (PTO), points from fast breaks (PFF), points from second chances (PFSC), points scored from the paint (PFP), and points from the bench (PFBU).

All collected variables are normalized to ball possession (BP) multiplied by 100 (Zhou et al., 2024). Ball possession was calculated using the formula BP = (field goals attempted) – (offensive rebounds) + (turnovers) – 0.4 × (free throws attempted (Oliver, D. (2004). The matches were categorized into three types based on the final score difference: Closed games (final score difference of fewer than 10 points), balanced games (final score difference between 10 and 20 points), and unbalanced games (final score difference exceeding 20 points) (De Saá Guerra et al., 2013).

Statistical analysis

The descriptive statistics for winning and losing teams were presented as means and standard deviations for each round. Univariate differences among the predictor variables for winning and losing teams were evaluated using independent-sample t-tests. For the group stage, the second round, and the final round, a linear discriminant function was estimated for each game type (closed, balanced, or unbalanced), including, all predictors to identify the factors most significantly associated with the outcomes of specific game types. The cut of value for structure coefficients (SC) was established at an absolute value of 0.3 (*Finch, H. (2009*). The assumption of equality of covariance matrices was examined utilizing Box's M-test. A stepwise discriminant analysis was conducted to identify the predictors that optimally distinguished between winning and losing teams, employing subsequent F-tests as criteria for inclusion or exclusion, with *p*-values set at .05 and .1, respectively. The linear discriminant equation was applied to assign a discriminant score (D) to each team's game, represented by the equation D = βX, where β denotes the vector of estimated unstandardized discriminant function coefficients, and X represents the vector of obtained game-related statistics. The models' accuracy was assessed through leave-one-out classification (Iduseri & Osemwenkhae, 2015). Statistical analyses were carried out using the statistical package (IBM SPSS ver 26, Armonk, NY), and a significance level of 5% was established for all tests.

RESULT

The combined descriptive results of the 112 games of the Under-17 Basketball World Cup 2022 and 2024 are presented in Table 1.

Table 1. Descriptive statistics about the type of game per round.

Game Type	Group Stage		Second Round		Final Round	
	n = 49	%	n = 39	%	n = 24	%
Closed games	13	26.53%	11	28.20%	9	37.50%
Balanced games	10	20.40%	12	30.76%	6	25%
Unbalanced games	26	53.06%	16	41.02%	9	37.50%

The results of the group-stage matches of the Basketball World Cup showed that 53.06% (n = 26) of the games were unbalanced, 26.53% (n = 13) were closed, and 20.40% (n = 10) of the games were balanced. Furthermore, in the second round of the Basketball World Cup, the majority of games (n = 16) were unbalanced, while (n = 12) games were balanced and (n = 11) games were closed. Further, regarding the final round, 37.50% (n = 9) of the games were closed, 37.50% (n = 9) were unbalanced and 25% (n = 6) were balanced games.

Table 2: The Group Stage's key performance indicators with mean values (SD).

Performance Indicators	Closed (n = 13)		Balanced (n = 10)		Unbalanced (n = 24)	
	Winner	Loser	Winner	Loser	Winner	Loser
1Q#	25.20 (6.46)	26.24 (8.35)	36.415 (13.546)	25.43 (12.60)	38.72 (10.86)	19.88 (7.28)
2Q #	33.39 (18.28)	30.63 (11.37)	49.39 (19.9)	39.85 (16.02)	59.54 (20.08)	31.71 (13.87)
3Q #	43.88 (30.00)	35.76 (19.84)	72.75 (32.26)	56.50 (28.31)	78.76 (39.56)	41.57 (22.27)
4Q #	56.42 (46.83)	43.92 (36.38)	89.74 (47.64)	77.51 (44.74)	100.72 (59.24)	50.51 (30.96)
2P Try #	47.9 (18.66)	41.61 (10.72)	53.196 (6.40)	50.15 (15.47)	84.72 (14.68)	61.05 (12.20)
2P Made #	48.40 (13.02)	43.81 (19.42)	56.55 (23.23)	55.22 (24.27)	97.98 (54.50)	23.221 (9.093)
3 P Try #	33.08 (8.41)	33.17 (14.73)	41.19 (9.90)	34.00(8.46)	38.94 (7.58)	33.38 (10.26)
3 P Made#	20.19 (11.07)	27.2 (12.07)	28.122 (15.38)	26.11 (16.18)	12.36 (4.23)	6.10 (3.24)
FT Try #	17.81 (18.69)	13.21 (7.16)	26.06 (26.8)	17.24 (17.82)	36.98 (18.43)	25.65 (21.19)
FT Made#	27.17 (11.29)	24.16 (11.29)	31.0 (19.26)	31.22 (18.61)	24.33 (11.95)	15.451 (11.99)
OFR #	21.18(8.71)	17.62 (8.83)	20.99 (8.20)	20.24 (10.22)	31.29 (8.64)	18.67 (8.40)
DFR #	30.89 (24.69)	23.40 (13.22)	36.01 (18.13)	27.05 (9.02)	54.35 (12.99)	35.08 (11.69)
RBO(*,#)	53.83(28.59)	40.29 (14.013)	63.48 (19.91)	47.54 (11.01)	85.64 (17.83)	53.76 (17.83)
AST #	63.96 (39.03)	42.13 (15.425)	58.26 (27.26)	43.19 (25.77)	39.99 (10.88)	15.20 (6.40)
PF *	23.33 (7.34)	25.70 (6.90)	29.86 (12.35)	25.33 (12.84)	27.55 (12.44)	25.90 (9.35)
TRN(*,#)	25.30 (6.47)	23.03 (7.23)	35.65 (8.830)	27.21 (8.20)	22.42 (7.729)	34.49 (11.66)
STL #	17.26 (8.52)	19.37 (8.25)	21.18 (9.94)	26.11 (6.95)	22.99 (9.38)	11.82 (4.50)
BLK #	8.39 (5.55)	9.85 (5.65)	14.26 (6.00)	11.90(8.52)	9.33 (3.37)	5.27 (3.67)
PFT #	8.94 (7.31)	12.34 (12.83)	16.21 (10.66)	16.83 (15.424)	46.572 (21.18)	15.30 (8.29)
PFF #	20.006 (6.38)	19.911 (9.46)	31.64 (13.93)	19.96 (9.71)	44.82 (25.71)	17.59 (8.83)
PFSC #	22.84 (7.76)	18.757 (12.218	25.72 (11.27)	21.12 (6.4)	28.94 (11.420	15.17 (8.93
PFP #	27.977 (20.495)	21.132 (13.415)	36.58 (20.37)	33.14 (22.79)	83.97 (27.7)	43.58 (20.84)
PFBU #	35.063 (25.324)	40.923 (16.576)	60.45 (16.6)	51.74 (18.61)	76.66 922.72)	31.07 (15.54)

Note. Significant univariate differences between winning and losing teams in closed games ($), balanced games (*), and unbalanced games (#) (p < .05).

Group stage

The performance indicators of all the games from the group stage matches are listed in Table 2. From the univariate analysis of 13 closed games, it has been found that there was no significant difference between the winning and losing team's games in the group matches. The teams that dominated in a closed game to win the group stage averaged 2.76 points in the second quarter, 8.12 points in the third, and 12.5 points in the fourth. The descriptive result showed that the field goal try (p = .010), rebound (p = .040), turnover (p = .040), and point from fast break (p = .043) were the most significant indicators in the case of balanced games. In unbalanced games, all the indicators except personal foul (PF) have significant difference between winning and losing teams in the group stage.

Table 3. Structure coefficients of predictors at the Group Stage according to game type (closed, balanced, or unbalanced).

Performance Indicators	Closed game	Balanced game	Unbalanced game
1Q	**0.5**	**0.52**	**0.489**
2Q	-0.256	0.259	0.204
3Q	-0.003	0.121	0.09
4Q	**-0.432**	0.037	0.066
Field Goal Try	0.285	0.266	**0.319**
Field Goal Made	**0.465**	0.089	**0.655**
2P Try	**-0.326**	0.144	**0.342**
2P Made	-0.062	0.137	0.15
3P Try	**-0.433**	0.084	-0.05
3P Made	**0.573**	-0.077	**0.318**
FT Try	**0.394**	**0.447**	0.11
FT Made	0.081	**0.314**	0.134
OFR	0.181	**0.694**	0.202
DFR	0.079	**0.522**	0.299
RBO	**0.481**	1	**0.308**
AST	**0.466**	0.233	**0.537**
PF	**0.38**	0.109	0.028
TRN	**0.321**	**0.55**	-0.159
STL	0.051	-240	0.291
BLK	0.114	**0.314**	0.244
PFT	0.151	-0.183	0.212
PFF	0.117	0.275	**0.484**
PFSC	0.099	**0.425**	0.18
PFP	-0.021	0.189	**0.382**
PFBU	**-0.516**	-0.092	0.266
Eigenvalue	0.803	0.458	7.051
Wilks lambda	0.555	0.686	0.124
Canonical correlation	0.667	0.56	0.936
Chi Square	8.842	6.596	99.077
p-value	.012	<.001	<.001

Note. Bold Numbers represent SC>.30.

Bold Numbers represent SC>.30

Table 3 shows the structural coefficient of the predictor in all the types of games. Points in the fourth quarter (SC = -0.432), field goals made (SC = 0.465), two-point tries (SC = -0.326), three-point tries (SC = -0.433), three-point made (SC = 0.573), rebounds (SC = 0.481), assists (SC = 0.466), turnovers (SC = 0.321), and points from the bunch (SC = -0.516) were the factors associated with winning closed games in the group stages.

For the closed games, the step-wise discriminate function was statistically significant and provided 69.20% of the overall variance of the game's outcome (Wilks' lambda = .555, $p < .001$). The standardized discriminant function of this reduced model, which included first-quarter scores and three points scored, revealed two predictors that best predict the game's outcome:

$$Dc = -7.036 + 0.150 \cdot 1Q + 0.109 \cdot 3PTM$$

The factors associated with winning balanced games in the group stage were the free throw try (SC = 0.447), offensive rebound (SC = 0.694), defensive rebound (SC = 0.522), the number of blocks (SC = 0.314), free throw made (SC = 0.314) and the points from the bench (SC = 0.425). For balanced games, the step-wise discriminant function was statistically significant and explained 70% of the overall variance in the game's outcome (Wilks' lambda = .686, p < .001). One predictor, the number of rebounds, was included in the reduced model, as indicated by the F-statistic. The discriminant function is:

$$Db = -3.880 + 0.058 \cdot REB$$

During the group stage, field goals made (SC = 0.655), assists (SC = 0.537), points scored in the first quarter (SC = 0.489), points from fast breaks (SC = 0.484), points scored in the paint (SC = 0.382), two-point field goal try (SC = 0.342), field goal made (SC = 0.319), and total rebounds (SC = 0.308) were the factors that contributed to winning the unbalanced games. The stepwise discriminant function analysis for unbalanced games was discovered to be statistically significant, accounting for 100% of the variance in game outcomes (Wilks' lambda = 0.124, p < .001). This model identified four key predictors that most effectively predict the game outcome, and the standardized discriminant function is as follows:

$$Dub = -8.283 + 0.083 \cdot FGM + 0.137 \cdot 3PTM - 0.025 \cdot Fttry + 0.058 \cdot DREB + 0.084 \cdot STL$$

The results showed that the discriminant function for closed games had a classification accuracy of 65.4% for the original group and 69.2% for the cross-validated data in terms of model accuracy. 75% of the original matches and 70% of the cross-validated data were correctly classified by the discriminant function for balanced games. Both the original group and the cross-validated group had 100% classification accuracy in the case of unbalanced games. The discriminant score histograms for winning and losing teams in closed, balanced, and unbalanced games are shown in Figure 1.

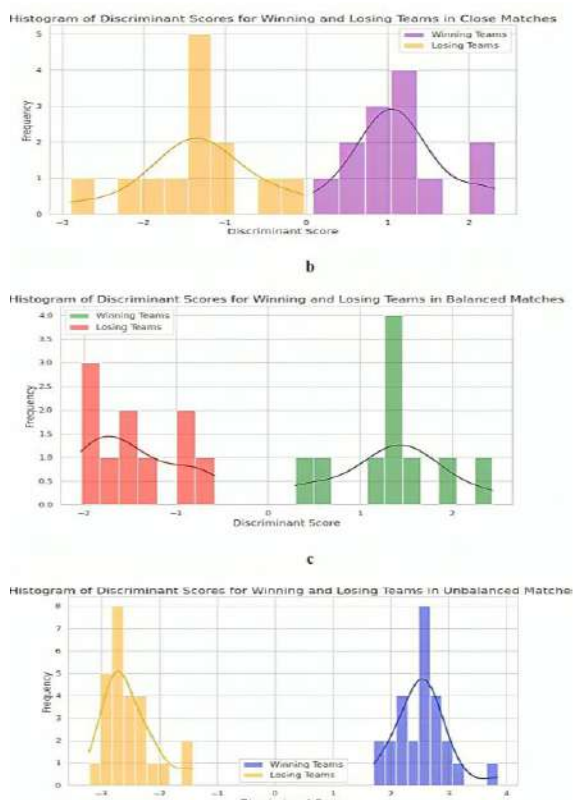

Figure 1. Discriminant scores for winning and losing teams in group stage games that are closed (a), balanced (b), and unbalanced (c)

Second round

The univariate differences of the predictor variables between winning and losing games of closed, balanced, and unbalanced games in the second round are shown in Table 4. The second-quarter scores of the teams indicated a higher trend for winning the game (p = .021). To be more precise, it was found that teams that dominated in a closed game scored 9.59 points higher on average in the second quarter. The significant difference in turnover (p = .024) and points from the bunch (.029) highlights the importance of ball control and bench strength in determining game outcomes. In balanced games, the univariate difference found that there was a significant difference in performance between the winning and losing teams in the performance indicators points scored in the first and third quarter (p = .027, p = .031), field goals made (p = .003), rebounds (REB) (p = .045) and assists (AST) (p = .042). This emphasizes the importance of both offensive and defensive contributions in-game success. In unbalanced games, the majority of key parameters showed significant differences between the winning and losing teams, except for three-point try, free throw try, free throw made, personal foul, and block.

Table 4. The Second-Round key performance indicators with mean values (SD).

Performance Indicators	Closed (n = 11)		Balanced (n = 12)		Unbalanced (n = 16)	
	Winner	Loser	Winner	Loser	Winner	Loser
1Q (#,*)	23.48(7.04)	25.08(5.02)	36.48(11.830	26.45(8.62)	38.12 (9.19)	18.21 (6.62)
2Q ($,*	31.22 (10.54)	21.63 (7.08)	34.87 (9.08)	36.00(13.54)	56.61 (23.85)	31.510 (12.51)
3Q (#,*)	24.86 (6.58)	24.06 (5.30)	28.97 (7.42)	46.11 (24.72)	76.50 (39.31)	46.45 (21.06)
4Q *	29.11 (6.47)	26.04 (10.08)	34.50 (8.99)	56.62 (36.58)	97.51 (55.22)	58.711(31.34)
2P Try*	49.31 (21.1)	49.76 (17.95)	65.19 (14.51)	60.59 (11.01)	70.63 (18.83)	56.20 (12.93)
2P Made *	38.84 (10.53)	44.53 (19.56)	34.64 (11.81)	28.65 (8.58)	114.85 (69.16)	22.83 (7.3)
3P Try	31.40 (12.98)	34.73 (8.28)	45.90 (15.13)	40.38 (11.12)	39.467 (10.05)	34.41 (10.85)
3P Made (#,*)	22.07 (11.71)	22.90 (13.97)	15.66 (6.7)	10.39 (4.5)	14.27 (5.110	7.9 (3.6)
FT Try	22.93 (17.6)	14.72 (11.6)	28.36 (12.29)	25.23 (13.17)	23.56 (11.27)	19.80 (12.10)
FT Made *	29.38 (9.1)	20.13 (11.63)	18.56 (8.38)	17.89 (10.16)	14.99 (8.03)	12.71 (9.24)
OFR *	22.78 (8.02)	19.78 (9.00)	23..05 99.01)	17.56 (7.98)	23.30 (9.44)	13.11 (5.42)
DFR *	31.28 (21.49)	35.49 (17.52)	47.59 (12.38)	40.82 (9.27)	49.24 (7.20)	34.99 (8.30)
RBO (#,*)	50.80(24.79)	52.90 (25.13)	70.64 (16.900	58.39 (10.63)	72.55 (12.78)	48.10 (11.55)
AST (#,*)	62.69 (29.67)	40.46 (21.78)	31.64(6.72)	25.41 (7.3)	33.94 (6.24)	16.92 (6.300)
PF	22.20 (6.27)	26.39(9.90)	24.52 (6.10)	25.52 (7.86)	21.86 (7.93)	22.02 (7.5)
TRN ($,*)	22.24 (4.25)	28.21 (6.89)	23.83 (7.48)	26.68 (11.64)	22.62 (8.6)	30.41 (10.26)
STL (*	18.10 (7.13)	16.39 (6.77)	14.67 (6.9)	13.56 (4.411)	18.95 (6.65)	12.30 (6.02)
BLK	9.5 (4.18)	8.33 (5.29)	6.49 (3.28)	4.44 (1.510)	7.09 (2.70)	5.38 (2.36)
PFT *	18.53 (16.23)	9.66 (9.81)	34.65 (15.80)	18.76 (6.99)	38.54 (18.22)	16.97 (9.82)
PFF *	21.47 (7.5)	19.16 (6.35)	26.53 (11.00)	22.014 (6.43)	31.63 (16.22)	13.29 (6.51)
PFSC *	21.88 (12.30)	23.15 (9.88)	20.20 (11.86)	14.35 (12.21)	25.46 (14.21)	11.49 (7.49)
PFP *	31.82 (22.245)	28.349 (15.22)	58.04 (18.15)	53.53 (16.30)	72.47 (26.13)	39.44 (13.57)
PFBU(#,*)	21.176 (20.27)	40.87 (19.04)	54.10 (22.21)	34.41 (25.8)	66.18 (17.27)	26.31 (13.51)

Note. Significant univariate differences between winning and losing teams in closed games ($), balanced games (*), and unbalanced games (#) (p < .05)

The structure coefficients of the discriminant function for the second round are presented in Table 5. An analysis of closed and balanced games revealed that no structural coefficients surpassed the established threshold of 0.30, suggesting that no individual factor had a predominant effect on game outcomes. In contrast, the factors associated with winning unbalanced games in the second round included field goals made (SC = 0.595), assists (SC = 0.522), points scored in the first quarter (SC = 0.478), points from the paint (SC = 0.470), points scored in the second quarter (SC = 0.450), turnovers (SC = -0.414), field goal try (SC = 0.372), two-point shots made (SC = 0.360), point from second chance (SC = 0.357), personal fouls (SC = -0.347), and points scored in the third and fourth quarters (SC = 0.331 and SC = 0.333, respectively).

Table 5. Structure coefficients of predictors at the Second Round according to game type (closed, balanced, or unbalanced).

Performance Indicators	Closed Game	Balanced game	Unbalanced game
1Q	-0.213	0.105	**0.478**
2Q	-0.074	-0.189	**0.45**
3Q	0.066	0.065	**0.331**
4Q	0.101	0.076	**0.333**
Field Goal Try	-0.116	0.112	**0.372**
Field Goal Made	0.15	0.218	**0.595**
2P Try	-0.034	-0.031	0.25
2P Made	0.117	0.086	**0.36**
3P Try	-0.258	0.15	0.083
3P Made	0.167	0.153	-0.009
FT Try	-0.154	0.039	-0.06
FT Made	-0.229	-0.094	-0.109
OFR	0.052	0.18	0.163
DFR	-0.135	0.036	0.298
RBO	-0.134	0.137	0.294
AST	-0.083	0.238	**0.522**
PF	0.069	0.129	**-0.347**
TRN	0.27	0.06	**-0.414**
STL	-0.158	-0.07	0.164
BLK	-0.063	-0.11	0.259
PFT	-0.25	0.205	0.137
PFF	0.127	0.154	0.282
PFSC	-0.201	-0.007	**0.357**
PFP	-0.074	0.041	**0.47**
PFBU	0.259	-0.03	0.263
Eigenvalue	4.099	11.006	7.212
Wilks lambda	0.196	0.083	0.122
Canonical correlation	0.897	0.957	0.937
Chi Square	29.322	47.223	60.01
p-value	<.001	<.001	<.001

Note. Bold Numbers represent SC>.30.

For the unbalanced games in the second round, the stepwise discriminant function was statistically significant and explained all of the variance in the game's outcome (Wilks' lambda = .122, $p < .001$). Three predictors were found to be the most accurate in predicting the game's outcome by this reduced model: points scored in the first quarter, assists, and a 2-point try. The discriminant function is:

$$Dub = -6.4420.073 \cdot 1^{st}Q + 0.124 \cdot AST + 0.018 \cdot 2PT$$

The results showed that the discriminant function could accurately predict 95.5% of the original and cross-validated closed games in terms of model accuracy. For the balanced games, the discriminant function correctly classified 95.8% of the cross-validated data and 100% of the original matches; for the unbalanced games, the cross-validated classification accuracy was 100%. Figure 2 displays the discriminant score histograms for winning and losing teams in closed, balanced, and unbalanced games.

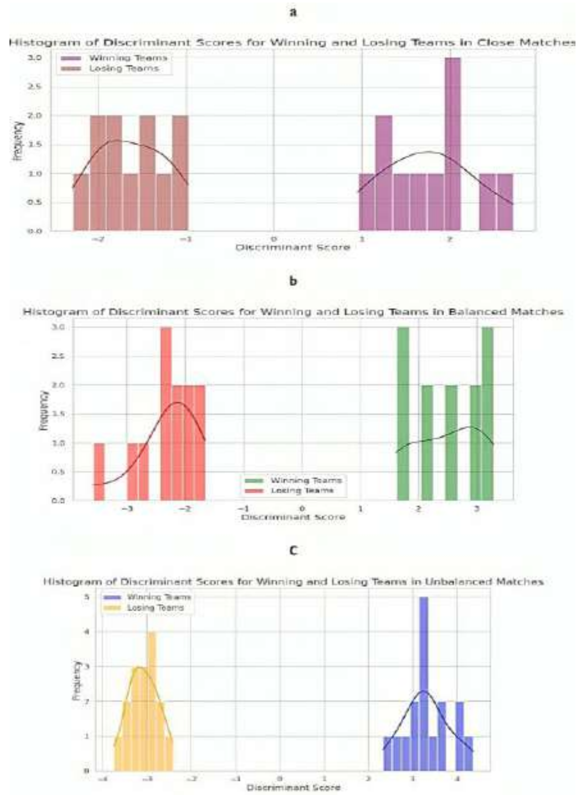

Figure 2. Discriminant scores for winning and losing teams in second-round games that are closed (a), balanced (b), and unbalanced (c).

Table 6. The Final Round key performance indicators with mean values (SD).

Performance Indicators	Closed (n = 9)		Balanced (n = 6)		Unbalanced (n = 9)	
	Winner	Loser	Winner	Loser	Winner	Loser
1Q *	29.14 (8.43)	26.89 (5.21)	32.37 (10.19)	27.78 (4.513)	40.73 (11.61)	22.78 (8.42)
2Q *	24.72 (7.49)	24.25 (6.17)	32.19 (9.34)	31.24 (13.03)	38.33 (10.63)	19.87 (8.43)
3Q *	27.85 (7.12)	23.65 (5.10)	36.21 (6.62)	37.76 (31.26)	42.43 (7.10)	25.233 (11.15)
4Q	26.14 (6.71)	23.27 (4.49)	41.91 (12.07)	37.76(31.26)	39.244 (10.12)	32.21 (11.58)
2P Try*	53.57 (22.62)	47.93 (14.75)	75.13 (17.96)	75.191 (13.79)	83.870 (9.49)	61.73 (12.43)
2P Made (#,*)	46.83 (18.04)	52.73(20.56)	39.44 (8.36)	30.08 (5.040)	103.24 (90.86)	25.60 (7.27)
3P Try *	28.67 (10.11)	30.75 (6.06)	32.831 (11.90)	37.25 (6.66)	37.53 (14.48)	37.16(4.84)
3P Made *	22.41 (12.01)	24.53 (16.52)	11.86 (5.870	8.63 (3.9831)	14.551 (6.26)	9.87 (3.81)
FT Try	20.11(14.4)	11.18 (6.280)	42.20 (21.13)	33.91 (13.95)	41.72 (23.04)	30.34 (26.17)
FT Made	25.59 (10.98)	19.68 (12.35)	28.22 (13.40)	21.67 (8.39)	27.69 (16.76)	18.92 (17.91)
OFR *	20.95 (10.95)	16.44 (4.148)	23.76 (6.99)	22.70 (5.74)	27.13 (7.411)	18.49 (7.37)
DFR(#,*)	26.64 (14.07)	32.27 (11.6)	59.21 (17.67)	37.51 (9.37)	52.12 (8.43)	39.18 (13.35)
RBO *	51.49 (14.60)	50.57 (15.37)	82.98 (22.07)	60.21 (12.00)	76.30 (16.74)	57.68(17.40)
AST (#,*)	74.57 (51.2)	47.60 (30.49)	33.34 (8.80)	21.85 (6.33)	41.17 (13.13)	25.00 (10.78)
PF	26.43 (5.64)	25.23 (4.45)	32.68 (8.78)	23.86 (8.79)	26.24 (13.44)	29.91 (11.66)
TRN *	24.44 (6.23)	29.28 (6.744)	14.03 (6.151)	17.72 (4.62)	22.42 (5.30)	31.74 (5.63)
STL *	21.00 (7.79)	16.65 (7.73)	17.72 (4.62)	9.85 (3.281)	23.93 (10.88)	10.77 (2.37)
BLK	11.86 (6.53)	12.29 (6.12)	9.85 (3.2)	6.15 (4.96)	8.32 (3.835)	6.67 (3.75)
PFT *	19.25 (18.04)	11.24 (6.33)	31.98 (9.06)	26.06 (11.05)	50.41 (22.33)	20.40 (10.23)
PFF*	20.21 (5.11)	16.40 (7.52)	29.92 (8.18)	21.86 (8.36)	54.52 (28.54)	22.63 (16.76)
PFSC *	19.70 (8.29)	21.98 (8.00)	19.19 (7.85)	22.51 (5.00)	25.64 (10.72)	14.546 (8.61)
PFP (#,*)	33.13 (26.021)	39.38 (21.66)	75.07 (16.20)	51.97 (7.63)	81.54 (29.06)	44.15 (15.43)
PFBU ($,*)	26.42(25.92)	47.60 (11.26)	61.77 (11.65)	43.02 (21.50)	67.27 (23.21)	37.90 (22.32)

Note. Univariate significant differences between winning and losing teams in closed games ($), balanced games (*), and unbalanced games (#) (p < .05)

Final round

In the final round, 24 matches were examined and divided into three groups: closed (n = 9), balanced (n = 6), and unbalanced (n = 9). Table 6, summarizes the performance metrics for the last round, contrasting the winning and losing teams. According to a univariate analysis of the nine closed games, the winning teams' bench players scored significantly fewer points on average (26.42) than the losing teams (47.60). The statistical analysis revealed a significant difference in scoring contributions from bench players between winning and losing teams (p = .031), suggesting that losing teams depend more on their bench players for scoring. In balanced games, the number of successful field goals differed significantly between winning and losing teams, with winning teams averaging 12.59 more successful field goals in the final round (p = .002). Additionally, the winning team recorded a greater number of defensive rebounds (p = .024), assists (p = .027), and points from the paint (p = .010). In unbalanced matches, all key performance parameters, except for fourth quarter score (p = .189), free throw try (p = .342), and made (p = .299), personal fouls (p = .545), and blocks (p = .372), did not have a significant impact on the outcomes of the games.

Table 7. Structure coefficients of predictors at the Second Round according to game type (closed, balanced, or unbalanced).

Performance Indicators	Closed Game	Balance Game	Unbalance Game
1Q	**-0.372**	**0.48**	**0.348**
2Q	**0.394**	0.151	**0.397**
3Q	0.023	0.214	**0.313**
4Q	**0.441**	**0.552**	**0.509**
Field Goal Try	**0.392**	-0.109	**0.375**
Field Goal Made	**0.477**	**0.757**	**0.742**
2P Try	**0.622**	-0.224	**0.633**
2P Made	**0.774**	0.249	0.086
3P Try	**0.636**	0.022	-0.184
3P Made	**-0.353**	**0.473**	-0.29
FT Try	**-0.459**	0.044	0.253
FT Made	**-0.346**	0.109	0.236
OFR	**-0.505**	-0.238	0.057
DFR	-0.04	0.068	0.065
RBO	-0.002	0.028	-0.046
AST	-0.017	**0.386**	**0.374**
PF	**-0.325**	-0.043	0.235
TRN	0.081	0.213	**0.381**
STL	-0.34	-0.45	0.053
BLK	**0.491**	-0.217	0.138
PFT	0.236	-0.021	**0.359**
PFF	**0.558**	**-0.337**	**0.417**
PFSC	0.133	0.13	**0.352**
PFP	0.099	**0.372**	**0.715**
PFBU	**0.712**	**0.541**	0.223
Eigenvalue	2.28	2.832	3.639
Wilks lambda	0.305	0.261	0.216
Canonical correlation	0.834	0.86	0.886
Chi Square	8.315	12.09	23.018
p-value	.016	.002	<.001

Note. Bold Numbers represent SC>.30.

The linear discriminant model, which included all parameters, found several factors related to winning closed matches in the final round (Table 7). These factors included two-point shots made (SC = 0.774), points scored from the bench (SC = 0.712), three-point try (SC = 0.636), two-point try (SC = 0.622), points from fast breaks

(SC = 0.558), offensive rebounds (SC = 0.510), blocks (SC = 0.491), free throw try (SC = -0.460), fourth quarter score (SC = 0.441), second quarter score (SC = 0.394), field goal try (SC = 0.392), first quarter score (SC = -0.370), three-point shots made (SC = -0.350), free throws made (SC = -0.350), and personal fouls (SC = -0.330). The stepwise discriminant function analysis for close games was statistically significant, explaining 100% of the total variance in-game outcomes (Wilks' lambda = 0.305, *p* = .016). This streamlined model identified two key predictors that most effectively forecast the game outcome: field goals made and total rebounds. The standardized discriminant function is as follows:

$$Dc = - 9.105 + 0.155\ FGM - 0.139\ REB$$

In the balanced games, the factors that influence winning the games were field goals made (SC = 0.757), points scored in the fourth quarter (SC = 0.552), points scored from the bunch (SC = 0.541), first quarter score (SC = 0.480), three-point made (SC = 0.473), Steal (SC = -0.450), points scored from assist (SC = 0.386), points from the paint (SC = 0.372), and the points from the fast break (SC = -0.337). For the balanced games, the stepwise discriminant function was statistically significant and explained all of the variance in the game's outcome (Wilks' lambda = .261, *p* = .002). The field goals try, and the field goal made is the two predictors that this reduced model found to be the most accurate in predicting the game's outcome. The standardized discriminant function is:

$$Db = - 3.525 - 0.059 \cdot FGTry + 0.223\ FGM$$

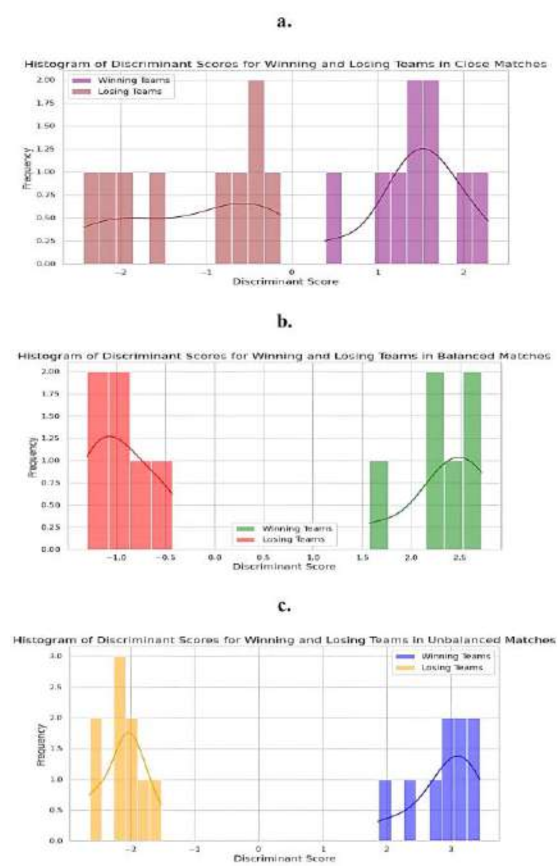

Figure 3. Discriminant scores for winning and losing teams in second-round games that are closed (a), balanced (b), and unbalanced (c).

For the unbalanced games in the final round main factors that influence the winning team are field goal try (SC = 0.742), point from the paint (SC = 0.715), two-point try (SC = 0.633), point scored in the fourth quarter (SC = 0.509), point from fast break (SC = 0.417), second quarter score (SC = 0.397), turnover (SC = -0.381), field goal try (SC = 0.375), assist (SC = 0.374), point scored from turnover (SC = 0.359), second chance point (SC = 0.352), point scored in the first and the third quarter (SC = 0.348), (SC = 0.313). For the unbalanced games, the stepwise discriminant function was statistically significant and explained all of the variance in the game's outcome (Wilks' lambda = .216, $p < .001$). The field goal made and the assist were the two predictors that this reduced model found to be the most accurate in predicting the game's outcome. The standardized discriminant function is:

$$\text{Dub} = -\,7.060 + 0.238\ \text{FGM} - 0.127\ \text{AST}$$

The results showed that the discriminant function can accurately predict 72.2% of the original and 77.8% of the cross-validated closed games in terms of model accuracy. While the original cases and cross-validated classification for the unbalanced games were 100% and 94.4%, respectively, the discriminant function for the balanced games correctly classified 91.7% of the original and cross-validated data. The discriminant score histograms for winning and losing teams in closed, balanced, and unbalanced games are displayed in Figure 3.

DISCUSSION

The purpose of this investigation was to find the key performance indicators that discriminate across different stages (group, second, and final round) of the under-17 basketball World Cups of 2022 and 2024. The analysis considered closed, balanced, and unbalanced games, allowing for an exact understanding of how different performance indicators contributed to game outcomes at various stages and identifying the primary predictor separating winning and losing teams. The study employed both descriptive analysis and stepwise discriminant function as methodology.

In closed games during the group stage, the dominant factors associated with the game's outcome are 3-point shots made, assists, and points scored in the fourth quarter. There was an interesting observation that the losing team made more 3-pointers (27.2) than the winning teams (20.19). These performance indicators highlighted that the trailing teams frequently employed a high-risk, high-reward tactic of increased three-point attempts to rapidly reduce the point gap. Furthermore, my finding was supported by (Csataljay et al., 2012). The winning team had a higher number of assists than the losing team in closed matches i.e. 42.13 versus 63.96 for the winning team. (Lorenzo et al., 2010) also mentioned the importance of assists in closed games. Victorious teams likely exhibit more effective passing strategies, creating better scoring opportunities and promoting a more offensive approach. This collaborative play style not only leads to more assists but also typically results in higher-percentage shots, contributing to the team's overall success in closed contests (Mukherjee et al., 2018). Furthermore, in closed matches in group stages, the winning team scored more points in the fourth quarter, 43.92, versus 56.42 for the winning. This pattern indicates that winning teams showed a high level of endurance and strategic execution in the crucial final period, maintaining momentum and building on their early lead. Particularly, in the last quarter, the winning team scored an average of 13 points more than the losing team.

Regarding the balanced games, the highest difference was found in the defensive rebound, points scored in the first quarter, and turnover. In balanced games in the group stages winning team took more defensive rebounds compared to the losing team. (Lorenzo et al., 2010; Çene, 2018) also found the importance of defensive rebounds in balanced games. Strong defensive rebounding enables teams to increase their offensive possessions while cutting their opponents' second-chance scoring opportunities. The points scored in the first quarter have also been a factor in winning the matches in balanced games. The team that establishes a strong lead early can maintain control throughout the game. The number of turnovers also showed an increase in the number for the winning team, which could be due to aggressive offensive strategies, resulting in errors. This confirms the earlier finding of (Madarame, 2018a) that teams that emphasize rapid transitions and employ high-pressure tactics frequently produce more turnovers; however, they can still achieve victory (Lorenzo et al., 2010).

In the group stage, unbalanced games were more unstable than closed and balanced games, and the winning team scored much higher on nearly every game indicator. The main difference was in the number of points from assists, rebounds, and fast breaks.

In contrast to the findings of (Stavropoulos et al., 2021b) regarding the 2019 Men's World Cup, which highlighted a combination of closed and balanced matches while excluding unbalanced ones due to fewer total matches in the second round, the under-17 World Cup has a different picture. In the second round of the U17 Men's World Cup, there was no clear dominant factor distinguishing closed and balanced games. This contradicts (Stavropoulos et al., 2021b) conclusions. In the context of unbalanced matches, key performance indicators such as assists and points from the paint emerged as critical discriminants for team success. The number of assists also showed an increase in the winning team, with seventeen assists more, on average, per game in the unbalanced game in the second round. It highlights the offensive capabilities of the team that wins the match but also underscores the importance of ball movement (García et al., 2014; Csataljay et al., 2012). In the first quarter, winning teams scored 38.12 points on average, while losing teams only scored 18.21 points, giving the winning teams a significant advantage of 19.91 points in unbalanced games. Successful teams, according to this trend, place a high priority on building early leads because it gives them an advantage in subsequent quarters.

In the final round, regardless of the game, the most important predictor was the points scored in the first and the fourth quarter, and the points from the fast break. The winning team scored higher in both the first and fourth quarters. Scoring early can boost confidence and influence subsequent play styles, which suggests that teams with a strong start tend to maintain momentum. In all kinds of games—closed, balanced, and unbalanced—points scored in the fourth quarter came as a predictor for winning the final rounds in a 2019 senior World Cup study (Stavropoulos et al., 2021b). The same pattern was observed in the present study. Points scored from fast breaks proved to be a significant predictor across all games. (Ortega et al., 2007). also found the importance of fast breaks in under 16 categories. Teams that were quick at fast breaks were able to switch from defence to offense, creating scoring opportunities before the opposing team could take up defensive positions. Fast breaks were a key element in deciding match results throughout the tournament; thus, the teams not only improved scoring efficiency but also controlled the game's overall tempo.

Beyond our primary findings, we identified several secondary determinants influencing match outcomes. Analysis of group-stage matches revealed that first-quarter scoring performance emerged as a crucial predictor of success in all types of games (closed, balanced, and unbalanced). Teams establishing an early scoring advantage demonstrated enhanced confidence and momentum, enabling them to focus more on scoring points in the upcoming quarters, which increased the probability of winning the game.

In the second round of closed matches winning team scored 18.53 points from turnover versus 9.66 points by the losing one. This supports the finding of (Lorenzo et al., 2010). Winners demonstrated a great ability to take advantage of their opponent's mistakes, with this significant difference in turnover points ultimately helping secure their victory. In balanced games, the most notable statistical disparity was observed in bench scoring performance (point from bunch). The winning teams' bench players scored an average of 54.10 points, while the losing teams' substitutes only scored 34.41 points. Maintaining a strong secondary unit and putting in place efficient rotation management techniques were strategically crucial, as evidenced by this notable 19.69-point difference. Points scored in the paint were found to be the secondary differentiator in unbalanced games. Winning teams had tried scoring close to the basket and relied less on shooting from the outside. Compared to the losing team, which scored 39.44 points, the winning team averaged 72.47 points inside the paint. The winning team, on average, scored 72.47 points from inside pain compared to the losing team, which scored 39.44 points in a single match.

In the final round of closed matches, the winning team won more fouls and had a higher free-throw success rate. It supports (Madarame, 2018a), who found that successful free throws discriminate between winners and losers in under 17 games. In balanced games, a higher difference was found in the number of steals. The Winning team has an average of 17.72 steals compared to the losing team of 9.85. Successful stealing not only breaks up the offensive flow of the opposition but gives the winning team a transition opportunity so they can take advantage of fast breaks. Furthermore, in unbalanced games, points from the paint came to be a secondary predictor.

CONCLUSIONS

In the group stage, first-quarter scoring was a consistent predictor of success across all game types. Closed games were influenced by three-point made and assists, while defensive rebounds and turnovers played crucial roles in balanced games. In unbalanced games, nearly all performance indicators, except personal fouls, showed significant differences between winners and losers. In the second round, points from turnovers were key determinants in closed games, while points from the bench had a strong association with winning balanced games. Unbalanced games were primarily influenced by points from the paint and assist, reinforcing the importance of inside scoring and ball distribution. In the final round, scoring in the first and fourth quarters, as well as fast-break points, emerged as deciding factors across all game types. The ability to start strong and maintain momentum in crucial phases of the game was a clear differentiator between winning and losing teams. These findings provide valuable insights for coaches and analysts to refine game strategies and targeted training programs. The study also highlights the evolving nature of youth basketball, where performance indicators shift across tournament rounds. Future research could explore these trends across different age groups and genders, incorporating additional variables such as player efficiency and tactical variations.

AUTHOR CONTRIBUTIONS

Akash Tom Mattakottil contributed to the conceptualization, methodology, investigation, data collection, formal analysis, and drafting of the original manuscript. Dhayalan K assisted with data collection and formal analysis. Dr. S. Jayaraman contributed to the review and editing of the manuscript, along with methodological insights and investigation. Dr. Viswanath Sundar provided validation, visualization, and formal analysis support. Kittu V.N. contributed to the formal analysis. All authors reviewed and approved the final manuscript.

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Comparison of snatch performance and barbell trajectory in elite weightlifters according to bodyweight categories

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ABSTRACT

This study was to compare the kinetic and kinematic differences in the snatch performances and barbell trajectory of the elite weightlifters. Two synchronized cameras recorded successful snatch performances during the 2010 World Weightlifting Championships. Weightlifters were separated into three bodyweight categories (BWCs) light weight (LWC), middle weight (MWC), and heavy weight (HWC). All performances were analysed using the Ariel Performance Analysis System. The Kolmogorov-Smirnov test was used for normality. A one-way ANOVA and Bonferroni correction post hoc test were used to determine group and subgroup differences. Relative barbell mass significantly decreased as the BWCs increased. Lower extremity angular movements showed similar performance outcomes in BWCs. As the BWCs increased, the barbell heights at the end of the first and second pulls significantly increased, and similarly, the maximum barbell height increased. There were no statistically significant differences in the horizontal movement of the barbell in all BWCs. In addition, the LWC lifted more heavy relative barbell mass than other WCs. Besides, HWC performed less relative power than others in the second pull. Consequently, lower barbell height and higher power output during the second pull might be clues for successfully lifting higher weights in the snatch technique.

Keywords: Performance analysis, Weightlifting, Snatch, Mechanical work, Power, Biomechanics.

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INTRODUCTION

Weightlifting is an Olympic sport that includes two main categories: the snatch and the clean and jerk, which utilise the entire body power. However, the strength of lower extremity plays a crucial role in lifting the barbell during the performance, especially snatch. Mastering the snatch lift requires both physical strength and a comprehensive understanding of kinematics, kinetics, and timing, making it one of the most technically demanding athletic skills (Arauz et al., 2025). Also, technique differences affect snatch performance (Arauz et al., 2024).

The Double Knee Bend (DKB) is used by weightlifters throughout the snatch performance (Baumann et al., 1988). DKB involves an extension-flexion-extension sequence and allows athletes to effectively use their legs to regulate and control movements. The kinematics of the DKB in the snatch are examined in five phases: as first pull, transition, the second pull, the turnover under the barbell and the catch phase (Baumann et al., 1988; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Hakkinen et al., 1984; Zahran et al., 2025). The kinetic and kinematic patterns between these phases may change. Therefore, the determination of kinetic and kinematic differences between the phases may help to explain elite or successful performance.

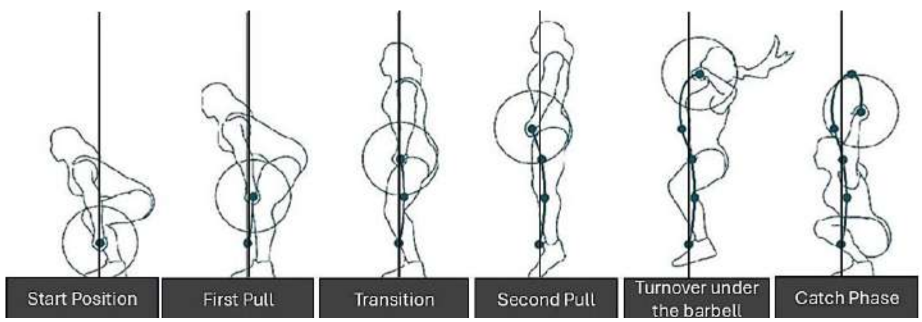


Figure 1. Phases of snatch (revised from study from Zahran et al. (2025))

The pull (from the start position to waist height) is the initial position of the snatch by lower extremity musculature (Arauz et al., 2024; Enoka, 1979, 1988; Geisler et al., 2023; Zahran et al., 2025). In addition to successfully performing, athletes need to have high muscular power and skill level in the snatch technique (Stone et al., 1998). Indeed, the snatch technique is related to the barbell kinematics and the athletes' kinematics and kinetics. The kinematic pattern of the total pull that is composed of the first pull, transition and second pull influences the success of the subsequent phases, including the turnover under the barbell and the catch phase (Baumann et al., 1988; Gourgoulis et al., 2000).

The technical skill is one of the most important factors in performance (Arauz et al., 2025; Liu et al., 2018). Because the technique used during the lift influences the trajectory of the barbell and its linear kinematics, resulting from the coordinated movement of the body and its segments, such as the angular kinematics of the lower limb (Baumann et al., 1988; Burdett, 1982; Gourgoulis et al., 2000), the trajectory of the barbell (Garhammer, 1982; Hoover et al., 2006; Schilling et al., 2002; Vorobyev, 1978; Whitehead et al., 2014) and the other mechanical factors (Arauz et al., 2024; Enoka, 1979; Garhammer, 1980; Gourgoulis et al., 2002). Moreover, power production of the athletes may be affected by small variations in the technique. And it can lead to an effect on the performance in the snatch.

The power production that depends on the body mass of athletes is limited (Garhammer, 1980; Lee et al., 2018). Therefore, the weightlifters race in different weight class. In addition, as the weight class increases, the kinetic and kinematics parameters during the snatch performance may affect due to the increased weight of the barbell (Ho et al., 2014). Therefore, the present study was to compare the kinetic and kinematic differences of the lower extremity and barbell trajectories between the snatch performances of elite weightlifters.

METHODS

Participants

The 52 male weightlifters who placed in the final groups during the 2010 World Weightlifting Championship (78th Men's and 21st Women's World Championships in Antalya, Türkiye) in the study. All participants signed an informed consent form to the Declaration of Helsinki. The weightlifters were separated 6 BWCs (56, 62, 77, 85, 94, and 105-kg). The categories were classified as light (56 and 62-kg, LC), middle (77 and 85-kg, MC), and heavy bodyweight category (94 and 105-kg HC)). The study was approved by the local ethics committee of the Faculty of Sport Sciences of the Selçuk University (Date and approval number: 28/01/2022, 22).

Experimental setup and data collection

All weightlifters performed the snatch lift on a platform. All successful performances of the weightlifters were recorded on an SD card in Audio Video Interleave (AVI) data type by two digital cameras (Sony DCR-TRV18E, Tokyo, Japan) at 50 Hz. The cameras were placed perpendicular to where diagonal of the movement area on the platform, as shown in Figure 2. A rectangular cube (length: 250 cm, depth: 100 cm, height: 180 cm) was used for calibration of the movement space on the platform.

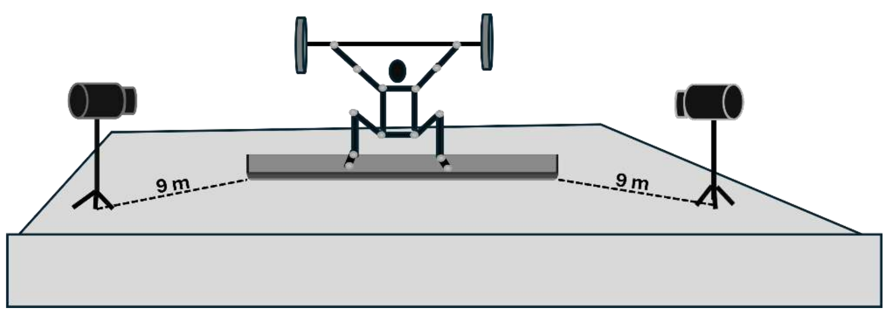


Figure 2. Experimental setup.

Data processing

The videos were transformed from AVI to JPG data type, being lossless. The Ariel Performance Analysis System (APAS, San Diego, USA) was used for digitization of each image. To synchronize the images obtained from two video cameras, the initial motion moment of the barbell from the ground was used for all performances. A point on the medial side of the right hand was determined to detect barbell trajectory. Five points on the right side of the body were digitized (5th metatarsal joint for the toe, the lateral malleolus for the ankle, the lateral epicondyle for the knee, the greater trochanter of the femur for the hip, and the greater tuberosity of the humerus for the shoulder) as manually using APAS software.

The 3-D spatial coordinates of the digitized points were calculated using the direct linear transformation (*DLT*) procedure of the analysis system with calibration image coordinates. The mean metric transformation error values were 2.9, 1.9, and 2.7 mm for the X-, Y-, and Z-directions, respectively. The raw data were smoothed using a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 4 Hz.

Calculation of the kinematic and kinetic parameters of the snatch performance

The phases were determined according to the change in the height of the barbell (Figure 3). The angular displacements of lower extremity joints (hip, knee, ankle) were calculated using Equation 1. To calculate the related angle, a, the length opposite the joint angle of segments. The *b* and *c* are other segments' lengths (proximal-distal) that compose the joint. The angular velocities of joints and the barbell vertical velocity were calculated using the central differences method (Equation 2). H_1: Barbell height at the end of the first pull, H_2: Barbell height at the end of the second pull, H_{max}: Maximum barbell height, H_{drop}: Drop distance from the maximum height of the barbell, D_1: Horizontal displacement toward weightlifter in the first pull, D_2: Horizontal displacement in the maximum height moment, D_3: Horizontal displacement toward backward after the beginning of descent from maximum height, V_1: Maximum vertical linear velocity of the barbell in the first pull, V_T: Maximum vertical linear velocity of the barbell in the transition phase, V_2: Maximum vertical linear velocity of the barbell in the second pull. *VRL*: Vertical Reference Line.

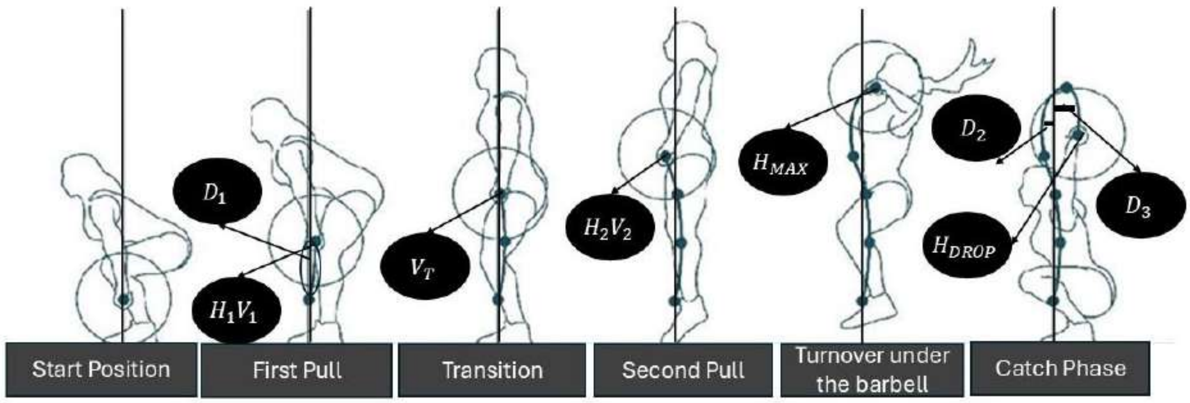


Figure 3. Phases and time instants for analysing the snatch (Zahran et al., 2025).

$$Cos\,\emptyset = \frac{b^2 + c^2 - a^2}{2bc} \qquad (1)$$

$$v = \frac{x_{i+1} - x_{i-1}}{\Delta t} \qquad (2)$$

Mechanical energy (*ME*) refers to the sum of the barbell's kinetic energy (*KE*) and potential energy (*PE*), which are calculated using Equations 3. Mechanical work done (*MW*) against gravity (*g*) was calculated from the changes in the barbell's mechanical energy (Equation 4) during the first ($ME_{1.\ pull}$) and second pulls ($ME_{2.\ pull}$). After the *MW* was calculated, the absolute power output (P_{absolut}) was calculated by dividing the work done during each phase by its duration (Δt). The relative work ($MW_{relative}$) and power ($P_{relative}$) values were calculated by dividing the absolute work and power values by the body mass (*BM*) in Equation 5.

$$PE = mgh\,, \qquad KE = \frac{1}{2}mv^2, \qquad ME = KE + PE \qquad (3)$$

$$MW_{absolut} = ME_{1.Pull} - ME_{2.Pull} \qquad MW_{relative} = \frac{MW_{absolut}}{BM} \qquad (4)$$

$$P_{absolut} = \frac{ME}{\Delta t} \qquad P_{relative} = \frac{P_{absolut}}{BM} \qquad (5)$$

Statistical analysis

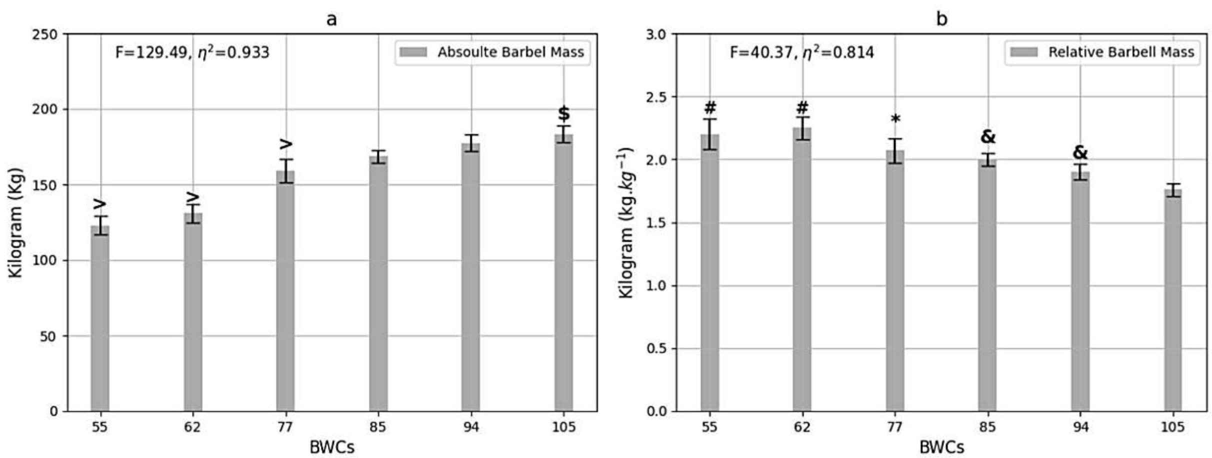
The descriptive data of weightlifters were presented in Table 1. To analyse normal distribution, the Kolmogorov-Smirnov test was used. The homogeneity of variances was tested using the Levene statistic. A one-way ANOVA was used to compare the kinetic and kinematic differences. Bonferroni correction was used as a post-hoc test for the subgroup analysis. Eta squared (η^2) was calculated to estimate the effect size (ES) for significant findings in ANOVA. The ES was examined as follows: $\eta^2 = 0.20$ – small effect, $\eta^2 = 0.50$ – medium effect and $\eta^2 = 0.80$ – large effect (Cohen, 1988). All statistical analyses were performed using the Statistical Package for Social Science version 15.0 (SPSS, Chicago, IL, USA). The level of significance was accepted as .05.

RESULTS

The comparison of absolute barbell mass (Figure 4a) and relative barbell mass (Figure 4b) showed significant differences according to BWCs. As the BWCs increased, the relative barbell mass decreased ($p < .05$). In addition, although absolute mass increases as BWCs increase, it was no significant differences between absolute barbell mass.

Table 1. The physical characteristics of elite male weightlifters in BWCs.

Body weight category	56 kg (n = 9)	62 kg (n = 8)	77 kg (n = 9)	85 kg (n = 9)	94 kg (n = 8)	105 kg (n = 9)
Age (years)	24.00 ± 2.12	25.38 ± 3.54	24.67 ± 2.96	24.89 ± 3.22	24.50 ± 2.67	27.22 ± 1.99
Body mass (kg)	55.81 ± 0.12	61.70 ± 0.17	76.68 ± 0.20	84.09 ± 0.80	93.18 ± 0.60	104.06 ± 0.53



*Note. $, different from 85-kg; #, different from 77, 85, 94, 105-kg; *, different from 94 and 105-kg, &, different from 105-kg, >, different from other BWCs, (p < .05).*

Figure 4. a) Comparison of absolute barbell mass results, b) Comparison of relative barbell mass results.

The angles of maximal flexion and extension of the joints during both pull phases revealed no significant differences (Figure 5a). However, the maximum extension angle of the knee joint was significantly greater in the 94-kg category than in the 56-kg and 77-kg categories during the first pull ($F = 4.56$, $\eta^2 = 0.331$, $p < .05$). In angular velocity analysis (Figure 5b), the maximum extension velocity of the knee joint in the second pull was greater in the 56-kg category than in the 105-kg category ($F = 2.53$, $\eta^2 = 0.215$, $p < .05$). In addition, the other angular kinematic parameters in the first pull, transition and second pull phases except for the knee joint, were not shown different.

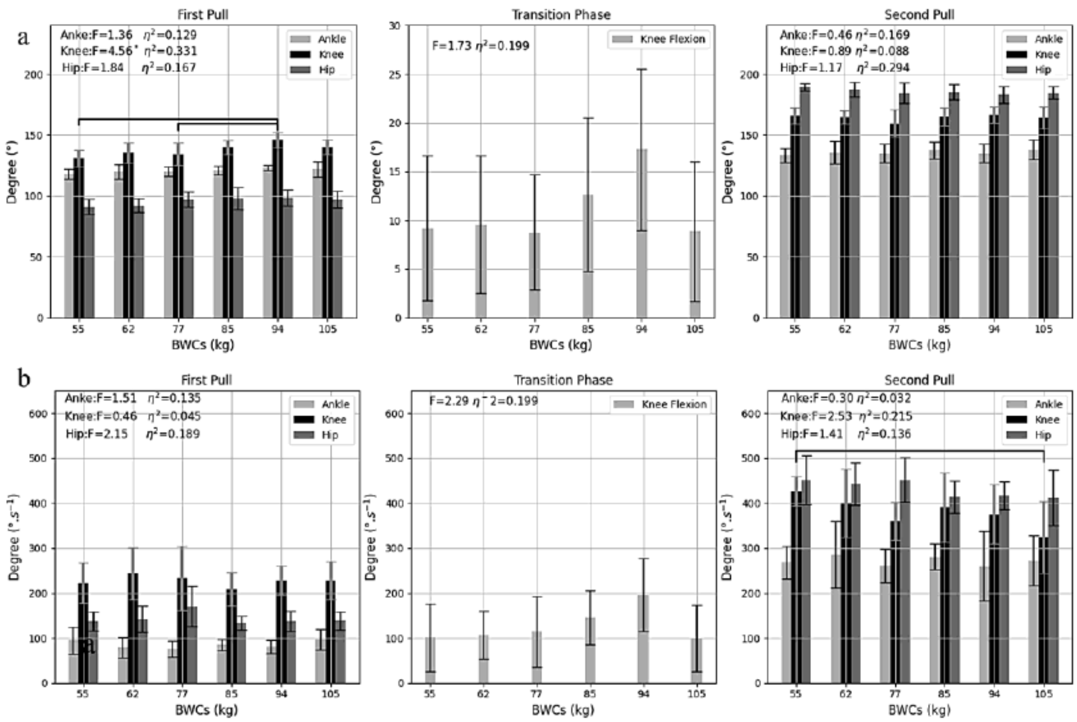


Figure 5. Angular displacement and velocity of lower limb joints in the first pull, transition phase and the second pull. a) Angular displacement of lower limb joints, b) Angular velocity of lower limb joints, $p < .05$.

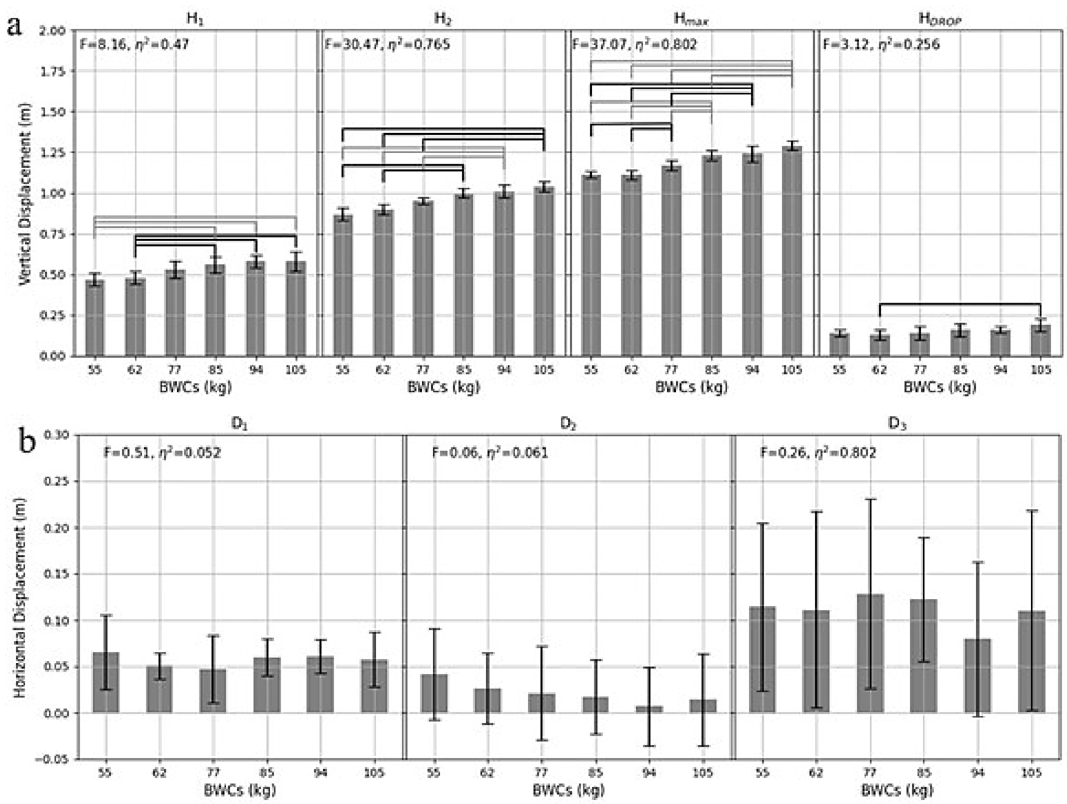


Figure 6. a) Vertical displacement of the barbell, b) Horizontal displacement of the barbell, $p < .05$.

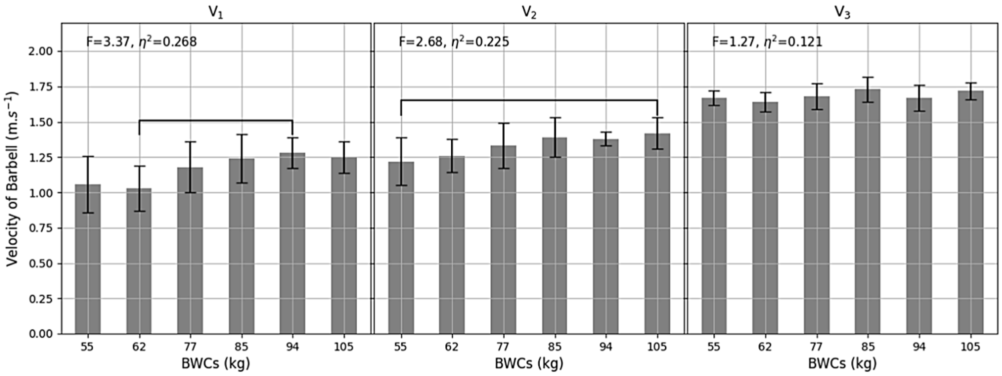
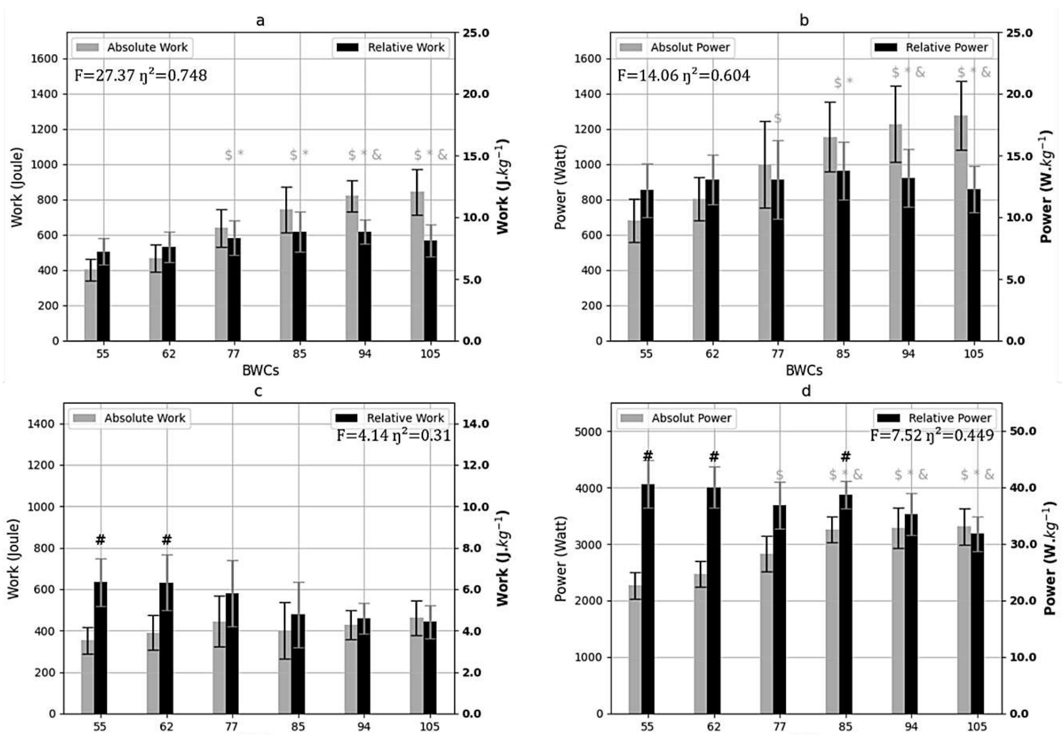


Figure 7. Vertical velocity of the barbell.

The barbell height showed significant differences. The H_1 was low in the 56 and 62-kg BWCs, according to other BWCs (F = 8.16, η^2 = 0.470, p < .05). H_2 and H_{max} were high as the BWCs increased (F = 30.47, η^2 = 0.765, F = 37.07, η^2 = 0.802, respectively). In addition, H_{drop} was different in the 105-kg from the 62-kg (Figure 6a).

Besides that, in Figure 6b, there were no significant differences in the horizontal displacement D_1, D_2 and D_3. In addition, although it was differences in the V_1 and V_T, these differences did not have high effect size. Also, the V_2 did not show statistical differences (Figure 7).



*Note. #; different from 105-kg, $; different from 55-kg, *; different from 62-kg, &; different from 77-kg. If symbols are bold style, the difference is in relative work and power results. If the symbols are grey style, the difference is in absolute work and power.*

Figure 8. Mechanical work and power output in the first pull and the second pull according to BWC. a) work results in the first pull, b) power results in the second pull, c) work results in the first pull, d) power results in the second pull.

Although MWabsolut and Pabsolut showed significant differences in the first pull, there were no significant differences in the Prelative and MWrelative (Figure 8a, 8b). As regards the second pull there were found differences in the MWrelative, Prelative, and Pabsolut outputs between BWCs (Figure 8c, 8d).

The analysis of the barbell trajectory in Figure 9 of every champion weightlifter in each BWCs showed that the H_{max} increased linearly as the weight class increased. And that the barbell moved intersecting the vertical reference line only in 62, 77, and 94-kg BWCs.

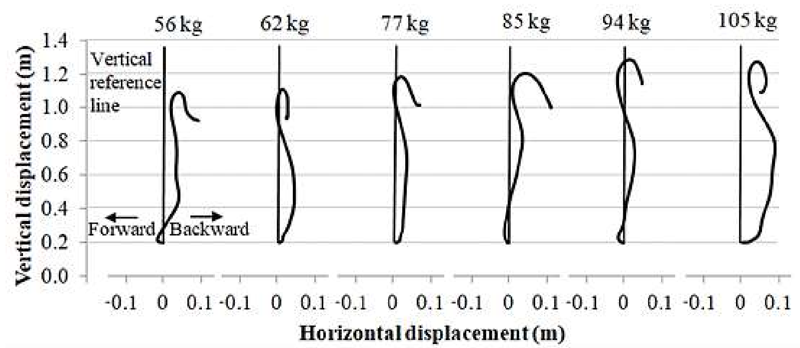


Figure 9. Barbell trajectories in the snatch lifts of the champion weightlifters.

DISCUSSION

The purpose of this study was to compare the kinetic and kinematic differences in snatch performances of elite weightlifters. As the BWCs increased, the relative barbell mass decreased. So, LWC lifted higher relative weights than MWC and HWC. However, according to $MW_{relative}$ and $P_{relative}$ in the second pull, LWC made more work and exhibited more power than 105-kg, HWC in championships. In addition, even if there were no significant differences in horizontal movement (D_1, D_2, D_3) and vertical barbell movement (V_1, V_T, V_2), the barbell height in H_1, H_2, H_{max} were shown significant differences according to BWCs. It was shown that when the WCs increased, the barbell height increased as the natural result of the weightlifters' physical differences or body sizes as reported by Arauz et al. (2025), Vidal Perez et al. (2021) and Shalmanov et al. (2015).

The DBP involves re-bending the knees during the transition phase after the barbell has been lifted above knee level (Kozub & Walker, 2022; Nagao et al., 2023). Therefore, the lower limb dynamic movements play an important role during the snatch. In the present study findings about lower limb kinetic and kinematic were not shown to have statistical differences. Cao et al. (2022) stated that elite weightlifters possess special technical characteristics. The techniques of successful snatch in the current study had a similar pattern in lower limb kinematics and kinetics. All participants were to perform that included special techniques to their maximum to become champions in the championship. And all of them were elite weightlifters. These finding were supported that report of Cao et al. (2022). Thus, it can be said about a successful lift: the successful snatch has to similar pattern during the perform as regards from BWCs.

In the snatch technique, the bar makes primarily three horizontal movements in all three trajectories. The first is toward the lifter in the first pull, the second is away from the lifter during the second pull, and the third is toward the lifter after the barbell starts to descend from the maximum height (Campos et al., 2006; Garhammer, 1993; Hoover et al., 2006; Schilling et al., 2002; Vorobyev, 1978; Whitehead et al., 2014). In the present study, the trajectory of the barbell did not cross the vertical reference line during the first pull. However, during the second pull, the trajectory intersected the vertical reference line in 24% of the LWC, 33% of the MWC, and 47% of the HWC. On average, this accounted for 35% of all lifts. The amount of forward and backward horizontal movement in the snatch technique is considered one of the most important factors influencing technical efficiency, the force applied to the barbell, and ultimately the overall success of the lift (Burdett, 1982; Garhammer, 1993; Isaka et al., 1996; Nagao et al., 2023; Stone et al., 1998). Lifting the barbell to a lower maximum height is associated with flexibility and technical skill and is considered important for successful snatching (Bartonietz, 1996; Burdett, 1982; Gourgoulis et al., 2002). World-class weightlifters gain an advantage by lifting to a lower maximum height and lowering their bodies faster, while athletes in the HWCs have a significantly higher average maximum barbell height (Burdett, 1982; Kipp et al., 2024). This suggests that LWC may have an advantage in lifting relatively heavier loads, but body size, technique and flexibility are the determinants of maximum barbell height (Arauz et al., 2024; Bartonietz, 1996; Burdett, 1982; Garhammer, 2001). In addition, as seen in Table 4, the barbell height increased as BWCs increased, supporting the literature in the first and second pull. However, the horizontal displacement movements showed similar results in all BWCs. Nagoa et al. (2023) and Musser et al. (2014)'s results supported the present study results.

The lifter is relatively slow pulling the barbell during the first pull because lifters need to produce considerable work over a long period to overcome the inertia of the barbell (Gourgoulis et al., 2000; Sandau et al., 2022; Sandau et al., 2023). Thus, the first pull is strength-oriented, while the second pull is faster and power-oriented (Garhammer, 1991). Similarly in this study, mechanical work and power output in the first pull, as well as absolute power output in the second pull, were greater in the MWC and HWC than in the LC. In contrast, the relative power output in the second pull was greater in the LWC compared to the other categories. Several earlier studies that compared barbell and body kinematics across different BWCs reported that HWC tended to perform more mechanical work, lift the barbell faster, and generate higher power outputs due to the increased weight lifted (Garhammer, 1991; Garhammer, 2001; Kipp et al., 2011; Nagao et al., 2023; Sandau et al., 2022; Souissi et al., 2021). Campos et al. (2006) found that young male HWC (85 and 105-kg) were more efficient during the initial pull due to longer barbell pushing trajectories. LWCs were able to lift relatively heavier weights because they did not have the greater challenge that HWCs had to overcome. However, as the level of technical skill increases, unnecessary energy consumption can be reduced by maintaining optimal barbell height.

CONCLUSION

In the present study, no significant differences were found in the lower limb kinematics between BWCs, except for the greater knee extension velocity observed during the second pull in the LWC. These findings suggested that elite weightlifters had similar technical skills in high-level snatch performance. On the other hand, unlike HWC, LWC generated higher power output during the second pull even though they lifted heavier relative weights; this was related more to the lower maximum barbell height than to its vertical velocity. The reason is that LWC had an advantage in the snatch technique in terms of barbell height, so they needed more power than strength when compared to HWC. This observation suggested that lower barbell height and higher power output during the second pull might be clues for successfully lifting higher weights in the snatch technique. Therefore, training programs designed to increase power in the second pull and improve skill levels could help weightlifters lift heavier weights successfully.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the article's design, data collection, analysis and writing stages.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL CONSIDERATIONS

All participants signed an informed consent form during the championship in accordance with the declaration of Helsinki. The study was approved by the local ethics committee of the Faculty of Sport Sciences of Selçuk University (Date and approval number: 28/01/2022, 22).

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ORIGINAL ARTICLE

Breaking down success: Game-related statistical analysis in tennis grand slams

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ABSTRACT

The data-driven insights and examination of key performance indicators (KPI) in professional tennis is becoming increasingly popular and are now deemed important for player development and coaching strategies. The aim of the study was to analyse game-related KPIs differentiating winners from losers in the 2023 US Open and French Open tournaments. A total of 253 matches (127 men's singles matches from US Open and 126 men's singles matches from Roland Garros tournament) were included in the study. An independent t-test was employed to compare the differences between winners and losers for all indicators in 2023 French Open and US Open Grand Slams. For the variables that did not follow a normal distribution, the Mann–Whitney U test was used. Variables that showed significant differences between two groups were selected for discriminant analysis. It was found that winners outperformed losers in several key indicators, including Aces, Break Points Won %, First Serve % In, Net Points Won %, Receiving Points Won %, Second Serves In, Win % First Serve, and Win % Second Serve ($p < .01$, Cohen's d: 0.06-0.1, r: 0.02–0.85). In the context of the French Open, winners demonstrated a significantly higher percentage of win on First Serve (mean- 73.02, $p < .01$, Cohen's d:1.272), as compared to their counterparts who did not succeed and recorded a lesser percentage of win on First Serve (mean- 63.25, $p < .01$, Cohen's d:1.272). In conclusion, Serve quality, return performance, and error minimization are critical KPIs for success in Grand Slams. Surface dynamics play a significant role in shaping match strategies.
Keywords: Performance analysis, Game-related statistics, Tennis grand slams, Discriminant analysis, Coaching strategies.

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INTRODUCTION

The data-driven insights and examination of key performance indicators (KPI) in professional tennis is becoming increasingly popular among coaches and practitioners (Filipcic, Zecic, Reid, Crespo, Panjan, & Nejc, 2015;). Indeed, these data and KPIs are now deemed important for player development and coaching strategies (Klaus, Bradshaw, Young, O'Brien, & Zois, 2017; Cui, Gómez, Gonçalves, & Sampaio, 2018; Fitzpatrick, Stone, Choppin, & Kelley, 2019). The increasing demand of data and KPIs has led to numerous researches being conducted within the field of data analytics. Previous studies have investigated the player performance on varied surfaces (Cui et al., 2018), between different levels of players (Hizan, Whipp, & Reid, 2011; Klaus et al., 2017; Söğüt, 2017), sex ,age groups (R Cross, 2014; Hizan, Whipp, & Reid, 2015; Stare, Zibrat, & Filipcic, 2015), physiological responses (Reid and Duffield, 2014; Smith et al., 2018), stroke and movement characteristics (Hizan et al., 2015; Reid et al., 2016), and some aspects of performance (such as serving speed, serving efficiency, serving return) (Cross and Pollard, 2009; Hizan, Whipp, & Reid, 2011).

Amongst the various KPIs available, some KPIs are helpful in identification of success (i.e., winning), such as serve speed, return, net play, shot placement etc. (Filipčič, Filipčič, & Berendijaš, 2008; Fitzpatrick et al., 2019; Fernandez-Garcia et al. 2019), monitoring the parameters of a sport over time, on different surfaces (Cui et al., 2018), for varying playing positions (O'Donoghue P, 2004) and for long term development (Filipcic et al. 2021).

The annual four Grand Slam tennis tournaments—Australian Open, French Open, Wimbledon, and US Open bring together the top-ranked tennis players in the world. These elite athletes compete in a best-of-five sets format for men, navigating a challenging draw of 128 players. Analysing matches from these events provide a deeper understanding about the evolution of tennis tactics and strategies at the highest level, as well as the factors that contributes to match success. (Gillet et al., 2009; Reid et al., 2016; Woods et al., 2018, 2019, Cui et al. 2020).

Previous studies investigated the effectiveness of tennis players on different surfaces like clay and hard courts that influence the player performances (Fitzpatrick et al., 2019; Martin and Prioux, 2016; Lage et al., 2022). It was observed that fast surfaces like hard court induce shorter rally length leading to an aggressive style of play whereas slow surfaces like clay have longer rally and allow a more defensive style of play (Fitzpatrick et al., 2019) suggesting varying playing tactics. Therefore, identifying the performance indicators that contribute to success in a match is important to inform players, coaches and sports scientists about tactical, technical, and physical requirements of the most competitive situations and optimize training and match strategies (Fernandez-Garcia et al. 2019; Carlisle, 2021).

Given that the performance at the elite level can provide valuable insights for optimizing training and match preparation processes, it is essential to explore the competitive match-play characteristics. This understanding can offer practical implications, particularly for the players who are not succeeding, in this highly competitive game (Cui et al., 2017). It was hypothesized that winners would outperform losers in serve-and-return performance, break point conversions, net play, and overall efficiency.

METHODOLOGY

Sample and data

The study included a total of 253 matches from two Grand Slams tennis tournaments during the 2023 season. It included 127 men's singles matches from US Open and 126 men's singles matches from Roland Garros tournament. One match was excluded from the study due to the unavailability of complete match statistics on the web. The data were collected from the official website (https://www.rolandgarros.com and https://www.usopen.org/index.html) of the tournament following the process of previous studies (Cui, Gómez, Gonçalves, Liu, & Sampaio, 2017; Cui, et al., 2018). The game-related statistics for the matches played on the court covered with the Hawk-Eye camera system (Hawk- Eye Innovations, Southampton, United Kingdom) were included in the study. All the matches were played in accordance with the rules by International Tennis Federation (International Tennis Federation, 2020).

Performance indicators

The Key performance indicators (KPIs) selected for this study were adopted from the past literature (Gillet et al., 2009; Reid et al., 2016; Cui et al., 2018, 2019a). The raw match data were cleaned, organized, and evaluated to avoid misinterpretation of the player's performance and were divided into four categories representing the technical and tactical efficiency of the tennis players. Table (1) displays each performance indicator according to the following categories: serve points, return points, net points and winners and unforced errors.

The match outcome (win or lose) was the dependent variable and the performance indicators were selected as the independent variables for this study.

Table 1. List of variables analysed in grand slam tournaments in men's category.

Group	Indicators
Serve points	Ace (%), Double faults (%), First Serve In (%), Second Serve In (%), Win on first serve (%), Win on second serve (%)
Return points	Receiving points won (%), Break Points Won, Break Pts Attempt, Break Pts Won (%)
Net points	Net Points Won, Net Points Won (%)
Winners and unforced errors	Winners, Unforced Errors

Statistical analyses

Descriptive statistics (mean and standard deviation) were calculated for each performance indicator of winners and losers of the match, across different tournaments. The normality of the data was verified using Kolmogorov-Smirnov test, after which an independent t test was employed to compare the differences between winners and losers for all indicators in 2023 French Open and US Open Grand Slams. For the variables that did not follow a normal distribution, the Mann–Whitney U test was used instead.

To understand the differences for t-test, the standardized mean differences i.e. Cohen's d effect size was calculated and interpreted as d less than 0.2 trivial, d between 0.2 to 0.5 small, d between 0.5 to 0.8 medium and greater than 0.8 large effect (Hopkins et al., 2009). Whereas effect size for Mann–Whitney U test was calculated using the formula $r = z/\sqrt{n}$. The effect size was small if r is less than 0.3, r between 0.3 and 0.5 indicates medium effect, r greater than 0.5 means large effect (Karadimitriou, S. M., Marshall, E. & Knox, C. Mann-Whitney U Test (Sheffield Hallam University, 2018, Volker, 2006).

Variables that showed significant differences between two groups were selected for discriminant analysis. In a significant discriminant function, if the absolute value of the structural coefficient (SC) was greater than 0.30 (Sampaio et al., 2006), then a performance indicator was considered a meaningful contributor to differentiating winners from losers. The alpha level was set at $p < .01$ for all tests. All analyses were conducted using Statistical Package for the Social Sciences 24 (SPSS Inc., Chicago, IL, United States).

RESULTS

Table 2. Descriptive statistics.

KPI	French Open		US Open	
	Win	Loss	Win	Loss
Aces	6.07 ± 4.06	5.04 ± 4.92	10.36 ± 5.67	7.38 ± 6.36
Break Points Won	5.99 ± 1.82	3.08 ± 2.21	5.3 ± 1.74	2.09 ± 1.73
Break Pts Attempt	13.56 ± 4.55	8.74 ± 5.04	11.96 ± 4.69	6.23 ± 4.43
Break Pts Won %	46.45 ± 13.77	36.84 ± 23.08	47.92 ± 17.52	34.98 ± 27.78
Double Faults	3.78 ± 2.66	5 ± 3.15	3.68 ± 2.75	4.97 ± 3.08
First Serve % In	62.29 ± 6.67	60.38 ± 6.11	104.95 ± 33.92	110.08 ± 31.87
First Serve Attempts	113.32 ± 34.96	116.65 ± 32.23	64.67 ± 22.52	66.09 ± 20.5
First Serves In	70.52 ± 22.85	70.31 ± 20.27	49.54 ± 16.1	44.51 ± 16.55
Net Points Won	19.04 ± 8.95	18.46 ± 9.46	18.16 ± 9.25	15.59 ± 8.86
Net Points Won %	70.17 ± 11.53	63.59 ± 11.37	70.26 ± 9.63	61.32 ± 11.3
Net Pts Attempt	27.39 ± 12.82	28.71 ± 13.67	26.04 ± 13.22	25.26 ± 12.91
Receiving Pts Won%	45.9 ± 14.31	34.18 ± 5.6	42.76 ± 6.18	31.09 ± 5.44
Receiving Pts Attempt	115.46 ± 33.51	113.32 ± 34.96	110.08 ± 31.87	104.95 ± 33.92
Receiving Pts Won	50.55 ± 11.7	39.58 ± 15.87	45.88 ± 10.83	33.71 ± 14.56
Second Serves In	42.81 ± 15.43	46.35 ± 15.01	40.29 ± 14.63	43.99 ± 14.08
Total Pts. Won	NA	NA	117.12 ± 28.93	97.9 ± 35.6
Unforced Errors	36.18 ± 15.74	44.24 ± 14.84	31.91 ± 13.95	38.6 ± 12.88
Win % First Serve	73.02 ± 7.14	63.25 ± 8.19	77.65 ± 6.78	66.4 ± 7.9
Win % Second Serve	53.95 ± 9.44	44.42 ± 9.45	55.34 ± 9.36	43.66 ± 8.27
Win on First Serve	50.84 ± 15.36	45.03 ± 15.84	61.58 ± 7.26	59.87 ± 6.35
Win on Second Serve	22.93 ± 8.59	21.08 ± 8.98	21.91 ± 7.74	19.7 ± 8.4
Winners	39.47 ± 13.5	33.42 ± 15.67	39.12 ± 14.3	31.21 ± 15.46

Table 3. Results of independent t-test and Mann-Whitney U test along with its effect size.

Game Related Statistics	Independent t-test Sig. value		Mann Whitney U Test Sig. value		Effect Size (“*Cohens d*” or “*r*”)	
	French Open	US Open	French Open	US Open	French Open	US Open
First Serve % In	.019	.042	NA	NA	0.298^{s}	0.256^{s}
Win % First Serve	.000	NA	NA	.000	1.272^{l}	0.632
Win % Second Serve	.000	.000	NA	NA	1.010^{l}	1.323^{l}
Aces	NA	NA	.007	.000	0.170^{s}	0.296^{s}
Double Faults	NA	NA	.001	.000	0.206^{s}	0.234^{s}
Win on First Serve	NA	NA	.002	.013	0.194^{s}	0.157^{s}
Win on Second Serve	NA	NA	NA	.016	NA	0.151^{s}
Second Serves In	NA	NA	.042	.035	0.128^{s}	0.133^{s}
Net Points Won	NA	NA	NA	.016	NA	0.152^{s}
Net Points Won %	NA	NA	.000	.000	0.277^{s}	0.401^{m}
Break Points Won	NA	NA	.000	.000	0.609^{l}	0.692^{l}
Break Pts Attempt	NA	NA	.000	.000	0.467^{m}	0.550^{l}
Break Pts Won %	NA	NA	.000	.000	0.301^{m}	0.314^{m}
Receiving Pts Won	NA	.000	.000	NA	0.373^{m}	0.949^{l}
Receiving Pts Won%	NA	NA	.000	.000	0.657^{l}	0.757^{l}
Winners	NA	NA	.000	.000	0.242^{s}	0.302^{m}
Unforced Errors	NA	.000	.000	NA	0.288^{s}	0.499^{m}

Note: Effect Size “Cohens d” – for independent t-test; Effect size “r” – for Mann Whitney U Test; s – Small Effect Size; m – Medium Effect Size; l – Large Effect Size; NA – Not Applicable.

Tables 2 and 3 shows the descriptive statistics and comparison of the game related performance indicators between the winners and losers during the 2023 French and US Open.

It was found that winners outperformed losers in several key indicators, including Aces, Break Points Won %, First Serve % In, Net Points Won %, Receiving Points Won %, Second Serves In, Win % First Serve, and Win % Second Serve ($p < .01$, Cohen's d: 0.06-0.1, r: 0.02–0.85).

In the context of the French Open, winners demonstrated a significantly higher percentage of win on First Serve (mean- 73.02, $p < .01$, Cohen's d:1.272), as compared to their counterparts who did not succeed and recorded a lesser percentage of win on First Serve (mean- 63.25, $p < .01$, Cohen's d:1.272).

On the other hand, players in the US Open who emerged victorious recorded an average of 61.58 win on first serve, surpassing their opponents who won first serve with an average of 59.87.

The players who did not succeed (losers) committed more double faults and unforced errors. In the US Open, losers averaged 4.97 (r = 0.234) double faults per match, whereas winners averaged 3.68 (r = 0.234) double faults. Meanwhile, in the French Open, losers averaged 4.99 (Cohen's d = 0.206) double faults, while winners recorded an average of 3.78 (Cohen's d = 0.206) double faults per match.

Table 4. Discriminant function Structure Coefficients (SC) and tests of statistical significance.

Game related statistics	French Open	US Open
First Serve % In	-0.426	-0.105
Win % First Serve	0.337	0.280
Win % Second Serve	0.399	-0.402
Aces	-0.171	0.148
Double Faults	-0.066	-0.035
Win on First Serve	0.806	0.631
Win on Second Serve	#	-0.402
Second Serves In	-0.863	-2.271
Net Points Won	#	0.026
Net Points Won %	-0.121	0.200
Break Points Won	0.863	0.676
Break Pts Attempt	0.019	0.062
Break Pts Won %	-0.069	-0.174
Receiving Pts Won	-0.389	-0.560
Receiving Pts Won%	0.211	0.542
Winners	0.356	-0.065
Unforced Errors	-0.274	-0.076
Eigenvalue	1.658	2.692
Wilks Lambda	0.376	0.271
Canonical Correlation	0.790	0.854
R^2	62.41	72.93
Chi-Square	237.071	318.044
Significance	<.001	<.001
Reclassification	90.9%	94.1%

*Note. *SC discriminant value ≥|.30| # means that variable was non-significant and was not used in discriminant analysis.*

The discriminant functions (see Table 4) recorded in this study were highly effective in distinguishing winners from losers, as evidenced by the reclassification rates of 90.9% for the French Open and 94.1% for the US

Open. The high r2c values (0.62 for the French Open and 0.73 for the US Open) reflects the robustness of these functions.

The indicators that significantly contributed to the discriminant functions during the French Open included: First Serve %, Win % First Serve, Win % Second Serve, Win on First Serve, Second Serves In, Break Points Won, Receiving Pts Won, and Winners with |SC (Structural Coefficient) | values ranging from 0.33 to 0.86.

Conversely, across the US Open, the indicators that contributed to the discriminant functions were Win on First Serve, Win on Second Serve, Second Serves In, Win % Second Serve, Break Points Won, Receiving Pts Won, and Receiving Pts Won%, with |SC| values ranging from 0.40 to 2.27.

DISCUSSION

Tennis is evolving rapidly because of the advancement of technology in tennis equipment (Allen et.al. 2016; Haake & Coe, 2000) and scientific sports training which has enabled the players to hit faster strokes and improve fitness. Therefore, it is important to constantly analyse the variables that affect performance. The primary objective was to identify key performance indicators that distinguish winners from losers across various matches in 2023 French and US open tournaments. The results of this study illuminate critical performance differentials between winners and losers in the 2023 French and US Open tennis tournaments. Notably, the superior performance of winners across several key indicators underscores the multifaceted nature of success in high stakes matches.

Serve performance

Winners significantly outperformed losers in metrics related to serving, such as Aces, First Serve % In, Win % First Serve, and Win % Second Serve. This research underscores the crucial role of serve quality in determining match outcomes (Cui et al. 2018), which indicates the control of the serve situation, effects, direction and hitting power.

O'Donoghue and Brown (2008) reported that servers in men's singles Grand Slam matches won 62.4% of points lasting shorter rallies, compared to 49.7% for points with 5 or more shots. This advantage was most notable in points comprising 3 to 4 shots on the first serve and 1 to 2 shots on the second serve (O'Donoghue & Brown, 2008). Ziagkas et al. (2017) also emphasized on the accuracy of the first serve at the French Open from 2002 to 2009 that increased from 60.2% to 64.2%. Furthermore, an increase in the percentage of first serves won by one unit makes a player 1.27 times more likely to win the match, while an increase in the percentage of second serves won by one unit increases the likelihood of winning by 1.17 times (Ma, Liu, Tan, & Ma, 2013). Additionally, a player who serves, on average, more than 5 aces is likely to win the match. However, the number of Aces did not contribute significantly to the discriminant functions in this study. This suggests that players at the highest level adopt more consistent and similar approach to serve performance. The high effectiveness of first serves, both in terms of landing in and winning points, suggests that a robust first serve not only initiates play favourably but also sets a psychological tone. Similarly, consistent second serves reduce the risk of double faults, thereby maintaining pressure on the opponent.

Serve return

Studies consistently highlights the critical role of serve return in determining competitive success (Cui, 2010; Elliott, & Saviano, 2001). The significant difference in Receiving Points Won % (0.389-0.560) highlights the comprehensive skill set of winning players. Statistically, increases in the percentage of points won on first and second serve returns significantly correlate with higher likelihoods of winning matches. An increase in the percentage of first serve return points won by one unit corresponds to a 1.16-fold higher likelihood of winning the match. Similarly, an increase in the percentage of second serve return points won by one unit correlates with a 1.15-fold higher likelihood of winning the match. The reason for this could be firstly, the losers are not consistent and show dominance in the first serve performance and secondly, there is a loss of efficiency in the second serve (Lage et al., 2023), which make the winners play more offensive strokes and take the initiative in setting the point in their favour.

In tennis, research has consistently shown that servers typically hold a substantial advantage over receivers in point-winning opportunities (O'Donoghue and Brown, 2008; Gillet et al., 2009). However, studies indicate that effective return of serves can mitigate this advantage and neutralize its benefits (Gillet et al., 2009; Ma et al., 2013).

Break points performance

The ability to convert break points is often a decisive factor in match outcomes, as it directly influences the scoring opportunities and pressure dynamics. The marked advantage of winners in Break Points Won (SC = |0.863| r = .301 in French Open and SC = |0.676|, r = .314 in US Open) indicates that winners were able to convert more break point opportunities and saved more break points on their serves. Furthermore, the discriminant analysis underlines the importance of Break point opportunities in influencing the likelihood of winning matches and putting a psychological pressure on the opponents while serving. A one-unit increase in break point saves corresponds to a 1.039-fold higher likelihood of winning the match. Similarly, a one-unit increase in break point conversions correlates with a 1.032-fold higher likelihood of winning the match (Ma et al., 2013; Cui et al., 2018). The results of this study also correspond to the other studies on grass courts (Katić et al., 2011) and all Grand Slam surfaces for men (Ma et al., 2013). It will be useful for the players to incorporate more varied break point situations in their training in order to cope up with the stress and improve their game tactics.

Net performance

Net Points Won % was not able to discriminate between the winners and losers in the two Grand Slam tournaments. However, the winners in the US Open has shown exceptional net performance with higher Net Points Won % ($p < .005$, r = 0.40). Previous studies by Cui et al. (2017 and 2020) and Djurovic et al. (2009) reported that many professional players heavily rely on net play strategies on fast courts. Proficiency at the net reflects versatility and adaptability in play, allowing winners to disrupt opponents' rhythm and shorten points effectively.

Winners and unforced errors

The finding suggests players who served fewer than two double faults demonstrated a higher likelihood of winning matches compared to those who served between three to five and more than six double faults (Ma, Liu, Tan, & Ma, 2013). Filipcic et al. (2009) observed that losers in both genders tend to commit more unforced errors than winners, who also achieved a greater number of winners. These studies identified playing errors, such as unforced errors and double faults, as critical factors influencing match outcomes (Martínez-Gallego et al., 2013; Djurovic et al.,2009). Cui (2018) has also reported that the ability to hit more winners and making less unforced errors is basis for technical and tactical efficiency, physical fitness and mental toughness.

The discriminant functions developed in this study were highly effective in distinguishing winners from losers, as evidenced by the reclassification rates of 90.9% for the French Open and 94.1% for the US Open. The higher |SC| values observed in the US Open compared to the French Open suggest that the variability and impact of these indicators are more pronounced on the faster hard courts of the US Open. This disparity may be attributed to surface-specific dynamics, where aggressive play and serve effectiveness are more rewarded compared to the slower clay courts of the French Open (Collinson & Hughes, 2000; O'Donoghue & Ingram, 2001).

Implications for training and strategy

These findings have practical implications for coaching and player development. Emphasizing serve and return drills, particularly focusing on first serve accuracy and second serve reliability, can yield substantial competitive advantages. Drills to enhance the service consistency can be designed and decision-making under pressure situations should be incorporated in the training (Reid et al., 2013). Additionally, strategies aimed at improving break point conversion and net play could be integral to transitioning from competitive parity to dominance. Furthermore, analysing the shot patterns on different surfaces and opponent's game play can guide match preparation and make the player more adaptable to uncertainty (O'Donoghue, 2002). These findings can refine strategies, tactical approaches especially in high pressure situations like tie-breaks.

CONCLUSION

In conclusion, the study reaffirms the critical importance of serving, receiving, and error minimization in determining match outcomes at elite tennis tournaments. By elucidating the performance indicators that most significantly distinguish winners from losers, this research provides a nuanced understanding of competitive dynamics and offers actionable insights for enhancing player performance. Future research could further explore the interplay of these indicators across different surfaces and player styles, thereby enriching the strategic framework for achieving success in professional tennis.

AUTHOR CONTRIBUTIONS

Conceptualization, S.R, S.B and R.S; methodology, S.R.; data collection, S.B. and R.S.; formal analysis, S.R. and A.R; investigation, S.R. and A.R.; writing—review and editing, S.R. and A.R; project administration, S.R., S.B. and R.S. All authors have read and agreed to the published version of the manuscript.

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ORIGINAL ARTICLE

Ecological-dynamic approach in rhythmic gymnastics: Variation and variability for performance improvement

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ABSTRACT

The aim of the study is to compare, from an ecological-dynamic perspective, two run-up techniques (chassè and pre-jump) used to perform the split leap, aiming at improving performance in rhythmic gymnastics. The sample consists of six competitive gymnasts with an average age of 17.3 years (±1.9). The study used the integrated multifactorial optoelectronic system, consisting of six BTS Smart-DX video cameras, seven BTS-6000 force platforms, and fifteen passive markers. The results show that the jump performed with the chassè shows higher values in maximum amplitude (171.4° ± 16.5 vs. 167° ± 15.7) and maximum elevation (0.15m ± 0.03 vs. 0.14m ± 0.02) compared to the split leap performed with the pre-jump, even if, from the results obtained by the t-test, it emerged that this difference is not statistically significant ($p > .05$). Furthermore, the results of Cohen's Effect Size show a small effect size. In conclusion, from the results obtained in this study, it could be hypothesized that, since there are no statistically significant differences between the two run-up techniques, both could be used to vary the practice since they don't alter the jump performance. Variation in practice refers to the theoretical framework of the ecological-dynamic approach, which enriches the athlete's motor and technical skills.

Keywords: Performance analysis, Split leap, Run-up techniques, Integrated multifactorial optoelectronic system.

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INTRODUCTION

The ecological-dynamic approach defines sports performance as processes of continuous co-adaptations of athletes in space and time to identify the most functional action possibilities to achieve the goal (Duarte et al., 2012). According to this approach, the most relevant information for the decision-making process and action implementation emerges during the continuous interactions between the athlete and the environment (Travassos et al., 2012). Athletes, in fact, defined as complex systems, can exploit information from the environment, bringing out functional models of behaviour in performance contexts (Davids et al., 2013).

The theoretical framework of the ecological-dynamic approach lays the foundations for the study and interpretation of movement pattern variability in athletes (Seifert et al., 2013). Variability is essential because it provides the athlete with the necessary fluctuations (Davids et al., 2003) to adapt skills to the situation (Woods et al., 2020), developing the cognitive and motor spheres. In this way, the athlete can try out different variations of the movement rather than always repeating the same solution to the problem (Chow et al., 2011). In this regard, Bernstein (2014) coined the expression "*repetition without repetition*", that is, repeating the same problem-solving process but not the same solution.

Incorporating variation and variability into training is crucial to adapt the performance to the goal and the environment, prevent injuries and increase motivation, especially in rhythmic gymnastics which is described as a sport where there is a stereotypical repetition of gestures (Morgunova, 2020; Oltean et al., 2017). Rhythmic Gymnastics (RG) has been an Olympic sport since 1984 (Hamza et al., 2020) and is one of the few sports that is practiced only by women in most countries (Cleophas & Visser, 2024). The main characteristics of this sport are fluidity, elegance, harmony, strength, and dynamism (Coppola et al., 2024), expressed through the coordination of body movements with the handling of five apparatuses: rope, hoop, ball, clubs, and ribbon (Agopyan & Ors, 2023). A rhythmic gymnastics competition exercise consists of difficulties of body (DB), difficulties of apparatus (DA), dance steps (S), and dynamic elements with rotation (R). DB includes jumps, balances, and pivots. In this study reference is made to jump DB, considered by Chiriac et al. (2021) as very dynamic motor tasks that represent an essential component of RG performances (Polat, 2018; Santos et al., 2016). Jumps require complex muscular coordination of the lower and upper limbs (Ashby & Heegaard, 2002), strength, explosiveness, speed (Çimen, 2012), and flexibility, which is considered one of the fundamental motor skills in RG (Moraru & Rusu, 2016), as during the flight phase, the gymnast must maintain a fixed and well-defined shape of the DB to be performed (Di Cagno et al., 2008), accompanied by choreographic handling of the apparatus (Nazari, 2019).

The run-up is the phase preceding the jump and can be performed either with a run, especially in the early stages of DB learning, or with the chassè (Coppola et al., 2020). In recent years, a pre-jump (shown in Figure 1a) is also used in competition exercises to make the movement more fluid and faster, allowing for greater speed on the music. Varying the practice by using different run-up techniques enriches the athlete's technical skills, allowing to be flexible and adapt effectively to environmental demands (Newell & James, 2008). After the run-up, the jump involves the take-off phase, which is essential for generating the energy needed to jump. This phase can be performed with the take-off on one-foot or two-feet (Coppola et al., 2024; Akkari-Ghazouani et al., 2022). This is followed by the flight phase, in which the gymnast performs the jump with the possible handling of the apparatus, and the landing phase in which the athlete comes back into contact with the ground, cushioning the landing to avoid lower limb injuries (Błażkiewicz et al., 2019).

One of the favourite jumps by coaches and athletes in RG is the split leap (Örs & Turşak, 2020) that requires great speed, explosive strength, body control, and coordination (Mkaouer et al., 2012). During flight, the gymnast performs a sagittal split, bringing the dominant leg forward and the non-dominant leg back, reaching an amplitude of at least 180° at the highest point of the jump. It is preferable that the split position is horizontal, but the jump is also considered valid by the jury when the 180° amplitude is achieved with one leg above and the other below the horizontal position. This DB has a value of 0.30 points (Code of Points RG 2025-2028).

To enhance sports performance, it is important to investigate the dynamic and kinematic parameters of jumps, especially with technologies that allow for an accurate and detailed quali-quantitative analysis of the task, such as the integrated multifactorial optoelectronic system (also used in this study). In this regard, the study conducted by Coppola et al. (2023) investigated the effectiveness of using this system, considered the gold standard for motion analysis, to analyse the dynamics and kinematics of complex and fast motor tasks such as the split leap in RG.

In the scientific literature, there are studies investigating different aspects of the split leap in RG. In particular, the study conducted by Coppola et al. (2025) assessed the variability (CV%) in this jump performed free body and with the handling of the ribbon.

Aji-Putra et al. (2021) examined the relationship between the degree of flexibility of the lower limbs, the leg length of the gymnasts, and the height of the split leap.

The study by Örs & Turşak (2020) investigated some kinematic parameters of the split leap, including the amplitude and height of the jump, the flight time, the distance travelled during the jump, and the length of the last step. The study by Coppola et al. (2020) also investigated some kinematic parameters such as position, speed, acceleration of the sacrum and the amplitude of the jump, comparing two run-up techniques (chassè and run).

The research by Błażkiewicz et al. (2019) compared two different types of landing from the split leap, one stopped on one lower limb and the second with movements after the jump, to aim for improved performance, avoiding injuries.

However, there are no studies in scientific literature that investigate the pre-jump as a run-up technique for split leap in RG. For this reason, the aim of this study is to compare, from an ecological-dynamic perspective, two run-up techniques: chassè (widely used by gymnasts in competition and already studied in the scientific literature) and pre-jump (not yet investigated in scientific literature) used to perform the split leap to investigate the favourable biomechanical characteristics of jumps, aiming at improving performance in RG. It is hypothesized that the split leap performed with the chassè has greater results in elevation and amplitude than the pre-jump.

MATERIAL AND METHODS

Participants

The study sample consisted of six competitive gymnasts with an average age of 17.3 years (±1.9).

The average height value is 164.8 (±6.0) cm, while the average weight value is 54.7 (±3.6) kg.

The gymnasts belong to the following FGI (Italian Gymnastics Federation) categories: Junior 2 (n = 1), Senior (n = 5).

The gymnasts were randomly selected from a group of n = 20 athletes who took part in competitions during the sports year and who mastered the split leap technique. For all gymnasts, the dominant limb is the right.

The gymnasts trained three times a week for two hours a day and didn't report any injuries in the period prior to acquisitions.

The athletes signed the informed consent form, authorizing their participation in the study. In the case of underage athletes, the form was signed by their parents.

The study was conducted in accordance with the Declaration of Helsinki (2013) and has been approved by the Ethical Committee of the Department of Human Sciences, Philosophy & Education at the University of Salerno (protocol number: 0354235).

Instruments

The integrated multifactorial optoelectronic system consisting of six BTS Smart-DX video cameras, seven BTS-6000 force platforms, fifteen passive markers applied to the athletes' bodies following the Simple Helen-Hayes protocol, and two BTS-Vixta video support cameras was used for the study (BTS S.p.A., Italy).

Procedure

The study was conducted at the Laboratory for Innovative Teaching Methodologies and Analysis of Sports Performance, University of Salerno (Italy).

A preliminary pilot investigation was carried out to verify the correct administration of the motion analysis protocol in the same laboratory and on a sample similar to the one considered for the study.

A meeting was organized with the participating athletes (in the case of underage athletes with their parents/tutors) to provide all the necessary information regarding the study to be carried out.

Initially, the following anthropometric measurements of the athletes were taken: body weight, height, total leg length (measuring the distance between the anterior superior iliac spines and the medial malleoli), pelvis width (measuring the distance between the anterior superior iliac spines with a pelvimeter), pelvis height (taking the measurement perpendicular to a ruler placed parallel to the table passing through the greater trochanter and the anterior superior iliac spine), the diameter of the knee (measuring the distance between the femoral epicondyles of the knee) and the diameter of the ankle (measuring the distance between the medial and lateral malleoli) (Kadaba et al., 1990).

Subsequently, the gymnasts performed a standardized warm-up of the muscles involved in the chosen motor task, with reference to the muscle activation of the lower limbs.

Markers were then applied to the athletes' body following the Simple Helen-Hayes protocol (BTS S.p.A., Italy). Markers were placed on the S2, on the anterior-superior iliac spines, on the lateral femoral epicondyles, on the lateral malleoli, on the heels, and in the space between the second and third metatarsal heads. In addition, four rigid bars covered with markers were used and placed on the thighs (in alignment with the greater trochanter of the femur and the marker on the epicondyle) and on the legs (in alignment with the marker on the epicondyle and the one on the lateral malleolus), respectively, to avoid errors in the calculation of the hip intra-extra rotation and knee flexion-extension angles (Kadaba et al., 1990).

After performing a static acquisition with the subjects in orthostasis on the force platforms, five split leap trials with the chassè and five trials of the same task with the pre-jump were performed. Two minutes of recovery were given between the split leap with the chassè and the split leap with the pre-jump. All gymnasts performed a split leap with the right leg forward (dominant limb) and the left leg back.

Data analysis

A quali-quantitative analysis of the motor task was performed. Initially, through a qualitative analysis of the video, the three best jump trials in terms of well-defined form during flight were selected. Subsequently, we moved on to the quantitative analysis, using the SMARTtracker and SMARTanalyzer software (BTS S.p.A., Italy). The first allowed the reconstruction of the gesture, assigning a name to each marker according to the Simple Helen-Hayes protocol (as shown in Figure 2) and the identification of the Ground Reaction Force (GRF). With the SMARTanalyzer software, the modified Helen-Hayes calculation protocol was used to obtain the maximum jump amplitude (°) and the maximum elevation (m) data. In particular, the maximum amplitude was taken as the sum of the angles of hip flexion (for the front limb) and extension (for the back limb). The maximum elevation was calculated as the difference between the maximum height recorded by the marker on S2 after the take-off from the ground and the height recorded by the same marker at the take-off.

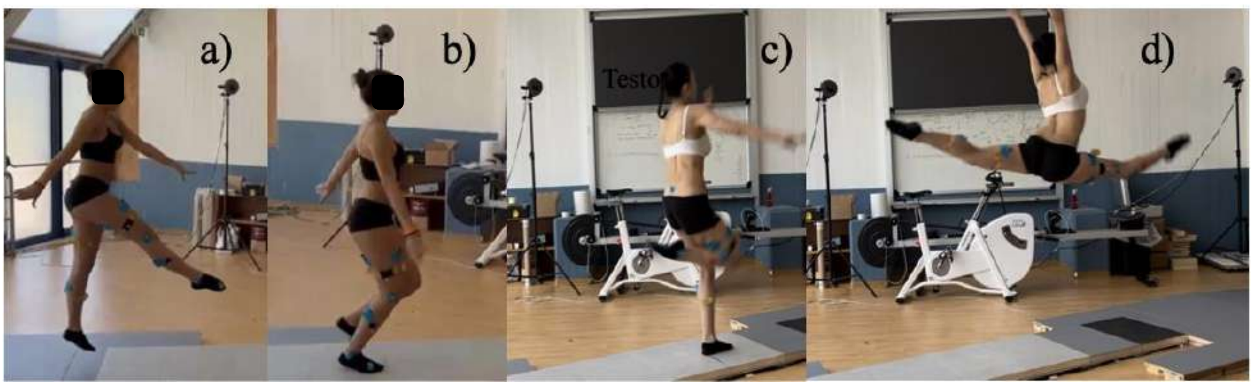

Figure 1. Representation of the phases of the split leap performed with the pre-jump: a) the pre-jump; b) the foot contact; c) the step forward with the opposite leg; d) the split leap.

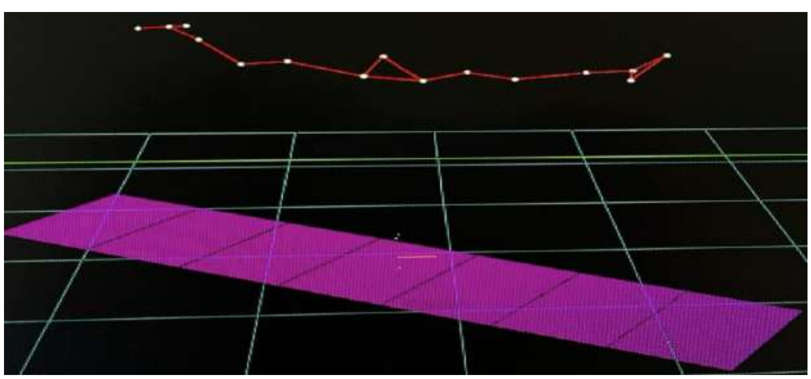

Figure 2. Representation of split leap with SMARTtracker software.

Using descriptive statistics, for each gymnast, the average values and the standard deviation (mean ± SD) of the three best jump trials were reported both for a split leap performed with the chassè and with the pre-jump. The mean and standard deviation (mean ± SD) of the whole sample were also reported for both the maximum split leap amplitude and the maximum elevation for the jumps performed with chassè and pre-jump.

Finally, with the MATLAB R2024b software (The MathWorks, Inc. 2024) the Cohen's Effect Size and t-test for the independent samples were used to verify if the difference between the mean values of the jumps made with the chassè and with the pre-jump was statistically significant.

Results

Table 1. Comparison of the group average of the maximum jump amplitude (°) performed with the chassè and the pre-jump.

Group average of the maximum jump amplitude performed with the chassè	171.4° ± 16.5
Group average of the maximum jump amplitude performed with the pre-jump	167° ± 15.7

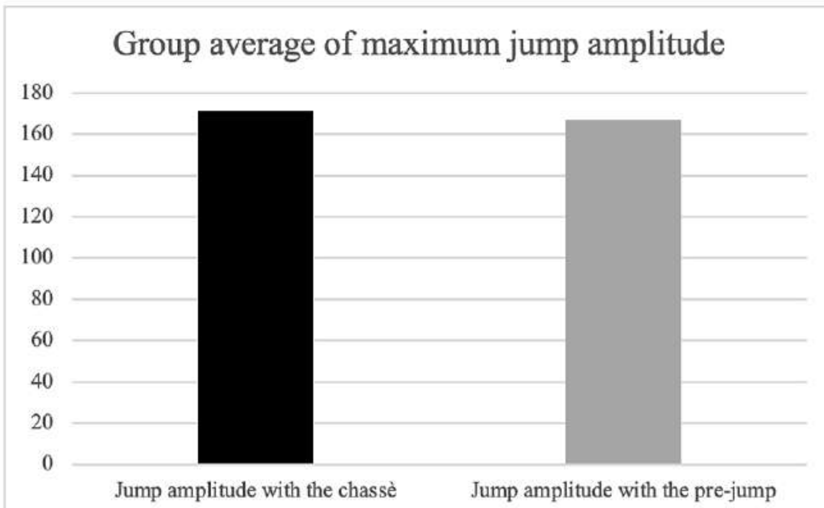

Figure 3. Graphic representation of the group average of the maximum jump amplitude (°) performed with the chassè and the pre-jump.

As shown in Table 1 and Figure 3, the average maximum amplitude (°) of the split leap performed with the chassè (black colour) is greater than the split leap performed with the pre-jump (grey colour) (171.4° ± 16.5 vs. 167° ± 15.7). Specifically, the difference in amplitude between the two run-up techniques is 4.4°.

Table 2. Comparison of the group average of the maximum jump elevation (m) performed with the chassè and the pre-jump.

Group average of the maximum jump elevation performed with the chassè	0.15 m ± 0.03
Group average of the maximum jump elevation performed with the pre-jump	0.14 m ± 0.02

As shown in Table 2 and Figure 4, the average values relative to the maximum elevation (m) of the jump performed with the chassè (black colour) are also higher than the jump performed with the pre-jump (grey colour) (0.15m ± 0.03 vs. 0.14m ± 0.02). In particular, the difference in terms of elevation is 0.01 m.

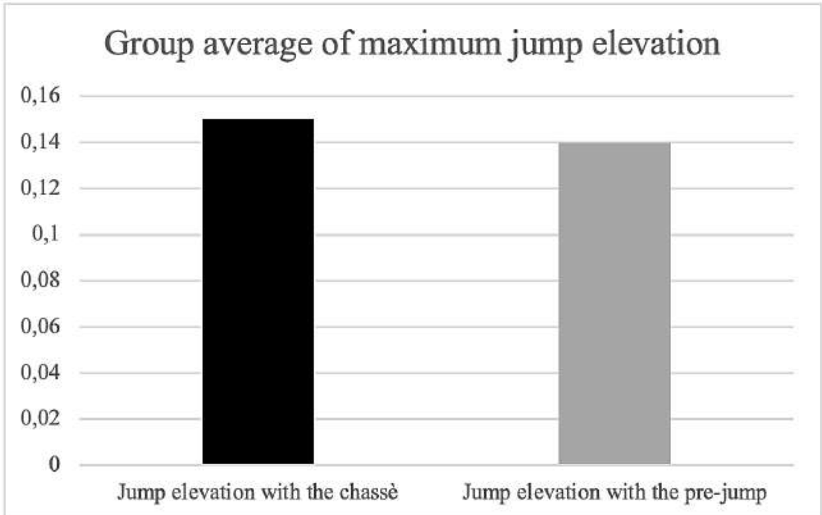

Figure 4. Graphic representation of the group average of the maximum jump elevation (m) performed with the chassè and the pre-jump.

Table 3. *p*-value of the independent samples t-test for the maximum amplitude and maximum elevation of the jump performed with the chassè and with the pre-jump.

***p*-value of the t-test of the maximum jump amplitude**	.6
***p*-value of the t-test of the maximum jump elevation**	.5

Table 3 shows the independent samples t-test *p*-values for the maximum split leap amplitude (0.6) and the maximum jump elevation (0.5).

Table 4. Cohen's Effect Size for the maximum amplitude and maximum elevation of the split leap.

Cohen's Effect Size of the maximum jump amplitude	0.4
Cohen's Effect Size of the maximum jump elevation	0.4

Table 4 shows the values of Cohen's Effect Size for the maximum amplitude and maximum elevation of the split leap performed with the chassè and with the pre-jump.

DISCUSSION

The purpose of this study is to compare, from an ecological-dynamic perspective, two run-up techniques (chassè and pre-jump) used to perform the split leap in rhythmic gymnastics (RG) to investigate the favourable biomechanical characteristics of jumps, aiming at improving performance.

From the results obtained, the jumps performed with the chassè have higher values in amplitude (Table 1 and Figure 3) and elevation (Table 2 and Figure 4) than those performed with the pre-jump (171.4°±16.5 vs. 167° ± 15.7; 0.15m ± 0.03 vs. 0.14m ± 0.02). These results are in line with the research hypothesis that split leap has higher results in elevation and amplitude with the chassè than the pre-jump. This could be because the run-up with the chassè, compared to the pre-jump, allows for the generation of a greater propulsion of the jump, and, consequently, the split leap could be better in elevation and amplitude. As described in the study by Marinho et al. (2021) chassè is a sliding step in which the back foot must catch up with the front foot as if chasing it. Upon contact with the floor, a countermovement is made that allows the hip, knee, and ankle muscles to actively extend and store energy. Next, the hips, knees, and ankles move rapidly into triple extension, and the muscles actively shorten, releasing energy (Weigand & Mokha, 2024). In this regard, the propulsion generated by the chassè is fundamental because, during the flight phase, the gymnast must have a fixed and well-defined shape of the jump (Code of Points RG 2025-2028; Di Cagno et al., 2008) to avoid penalties from the jury.

Although there are no studies in scientific literature that investigate the pre-jump as a run-up technique for split leap in RG, the results of this study are in line with the research by Coppola et al. (2020), in which split leap had a greater total elevation with the chassè compared to running, and also the hip flexion-extension angle was greater with the chassè. The study by Weigand & Mokha (2024), performed in dance, showed that the chassè is one of the most effective run-up techniques to perform the grand jeté jump. In this way, also in the study by Rice et al. (2021), it is described that, to perform a split leap, dancers typically use the chassè. Also, as described in the study by He et al. (2022) on table tennis, the chassè showed higher values in plantar force and peak pressure during the forward phase compared to a single step.

The results of the t-test (Table 3) show that the *p*-values are higher than .05 ($p > .05$), so there is no statistically significant difference (Mishra et al., 2019) between the two run-up techniques in maximum amplitude (0.6) and maximum jump elevation (0.5).

Furthermore, the results of Cohen's Effect Size (Table 4) show a small effect size according to McGuigan's study (2017). These could be due to the small sample size of the study (Garamszegi et al., 2012), which doesn't allow representative conclusions to be drawn for the population of gymnasts. The small sample size reduces statistical power and increases the probability of type II errors (Andrade, 2020), which could explain the lack of significant results despite some observed differences. The effect size is important because it provides a clearer picture of the difference between the groups (Kraft, 2020), which is crucial to understanding the practical significance of the results. Although a small effect size might suggest a slight difference between the two techniques, based on the data collected, it is not possible to conclude that one technique is superior to the other in a statistically significant way.

As there are no statistically significant differences between the split leap performed with the chassè and the pre-jump in elevation and amplitude, it could be hypothesized that both could be used because they provide different movement opportunities without altering performance. In this way, therefore, as described in the theoretical framework of the ecological-dynamic approach, it is important to vary the sporting practice to allow the athlete to adapt effectively to changing environmental demands (Woods et al., 2020; Araujo et al., 2020; Glazier & Davids, 2009; Davids et al., 2003), to prevent injuries (Nordin & Dufek, 2019; Bartlett et al., 2007; James, 2004), and to increase motivation (Bosch, 2021; Studenka et al., 2017), facing the monotony resulting from the stereotyped repetition of the same gesture, typical of gymnastics (Morgunova, 2020; Oltean et al., 2017). Variability provides the movement system with good adaptability and flexibility (Newell & James, 2008). Through variable training, in fact, athletes can try different variations of the movement (Chow et al., 2011).

Variation and variability are important because, especially in competition, the gymnast must make decisions and adjustments in her exercise as quickly as possible. Therefore, having a wide repertoire of choices allows the athlete to adapt to the situation as quickly as possible (McCosker et al., 2020). The ecological-dynamic approach highlights the importance of movement variation and variability in sport training to allow the gymnast to adapt performance to the environment and the goal to be achieved.

As for the practical implications, coaches should encourage gymnasts to try both run-up techniques to perform split leap, because, as described in the ecological-dynamic approach, it is important to adapt movements to both internal and external factors (Bartlett et al., 2007; Davids et al., 2003), allowing the gymnast to respond quickly to changing conditions and constraints. In this way, alternating between the chassè and pre-jump techniques can offer a significant advantage in developing a versatile, adaptable, and efficient movement pattern. The chassè could be used to maximize the effectiveness of the jump in terms of amplitude and elevation, while pre-jump could be used for the choreographic needs of the exercise or when the gymnast is too close to the red line on the floor and cannot cross it (otherwise the athlete would have a penalty from the jury). Trying both run-up techniques would lead to gymnasts being more flexible and adapting to different situations (Woods et al., 2020). In addition, the possibility of alternating between the chassè and the pre-jump could help to maintain high motivation and variety in training, reducing the risk of injuries due to repetitive movements, promoting a balanced, safe, and stimulating training for athletes.

CONCLUSIONS

The results of this study show that, although run-up with the chassè has higher values in terms of maximum amplitude and maximum elevation of split leap compared to pre-jump, the t-test shows that there are no statistically significant differences. Therefore, in line with the principles of variation and variability of the ecological-dynamic approach, both run-up techniques could be used to vary the practice without altering performance, reducing the risk of injuries and increasing the possibility of being flexible and adaptable to changes in the environment. Integrating both run-up techniques in the training program promotes a more complete preparation, in which the athlete is not bound to a single movement but develops the ability to adapt to changes, using the most suitable technique for the situation to perform an optimal jump.

The present study is not without limitations, as the small sample size, the acquisitions performed outside the training context (laboratory for human motion analysis), and the speed of the split leap, which required an accurate placement of the markers, blocked by applying tape around them.

In conclusion, future research perspectives in this field could be carried out on a larger sample belonging to different technical levels to investigate the favourable biomechanical characteristics of jumps, aiming at improving training and performance in rhythmic gymnastics. Further research could be carried out by investigating other techniques in rhythmic gymnastics to promote the variation in training and performance from an ecological-dynamic perspective.

AUTHOR CONTRIBUTIONS

The article is the result of a collaborative work by all the authors. CC and SC contributed to the preparation and research design, data collection, data analysis, result, interpretation and manuscript writing. RV is the scientific coordinator of the study. All authors have read and agreed to the final version of the manuscript and consent to its publication in JHSE.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL CONSIDERATIONS

These trials are conducted in accordance with ethical principles of the Declaration of Helsinki. Declaration of Helsinki: Ethical Principles for Medical Research involving human subjects (WMA, 2013). This study has been approved by the Ethical Committee of the Department of Human Sciences, Philosophy & Education at the University of Salerno (protocol number: 0354235).

CONSENT TO PARTICIPATE

The parents of the underage athletes signed an informed consent form, authorizing their participation in the study. The adult athletes signed the consent form autonomously.

DATA AVAILABILITY STATEMENT

Data available on request.

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ORIGINAL ARTICLE

Technical performance in the English Premier League: The influence of team quality and match location

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ABSTRACT

The purpose of this study was to compare the technical performance metrics of top- and bottom-tier English Premier League teams, examine the effect of match location on these metrics, and identify the statistically significant factors of winning. A total of 266 match observations were analysed via Mann–Whitney U tests and binary logistic regression. Top-tier teams had higher numbers in Shot, Shot on Target, Successful Take-On, Tackle Attacking 3rd, Pass Completed, Through Ball, Long Pass Completed, and Cross. Bottom-tier teams, on the other hand, recorded more Shot on Target Against, Clearance, Blocked Shot, Tackle Defensive 3rd, Yellow Card, Long Pass Completed %, and Aerial Duel Won. Generally, teams had increased offensive outputs in home games, while playing away primarily influenced defensive actions. For top-tier teams, each additional Aerial Duel Won and Shot on Target increased winning odds by 35% and 65%, respectively. Cross, Tackle Attacking 3rd, and Shot on Target Against decreased these odds by 30%, 43%, and 45%, respectively. Among bottom-tier teams, each event of Clearance increased odds of winning by 13%, while Shot on Target Against decreased them by 37%. These findings can be useful to coaches and performance analysts for evaluating and improving team performance.

Keywords: Performance analysis, Association football, Match analysis, Technical performance metrics, Match location.

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INTRODUCTION

Match analysis in association football, or simply "*football*," involves the objective recording of team activities and behavioural events in games, which aids in evaluating and providing feedback on both team and individual performance (Carling et al., 2005; O'Donoghue, 2009). This process allows teams to refine their strengths and address areas that need improvement. Likewise, by analysing an opponent's performance, coaches can devise strategies that neutralize that opponent's strengths and exploit their weaknesses (Carling et al., 2008).

A central element of such analyses is performance indicators: a set of selected variables that define some aspect of performance, establish an ideal profile necessary for athletic success, and contribute to the prediction of future outcomes in sport (Hughes & Bartlett, 2002; Jones et al., 2004). Hence, researchers have emphasized the importance of developing and utilizing these indicators (Carling et al., 2005; Carling et al., 2008; Hughes & Bartlett, 2002), and many studies have explored their relationships with match, seasonal, or tournament success (Andrzejewski et al., 2022; Bilek & Ulas, 2019; Castellano et al., 2012; Delgado Bordonau et al., 2013; Kubayi & Larkin, 2020; Lago-Ballesteros & Lago-Peñas, 2010; Lago-Peñas et al., 2010; Liu et al., 2015a; Liu et al., 2015b; Liu et al., 2015c; Liu et al., 2016; Mao et al., 2016; Stafylidis et al., 2024; Souza et al., 2019; Yue et al., 2014).

Within this field of research, performance metrics generally fall under two categories: physical and technical. Of the two, technical parameters (e.g., shots, passes, crosses) are widely regarded as more robust indicators of performance compared to pure physical activities, such as total distance covered, average speed, and average acceleration (Bush et al., 2015; Castellano et al., 2012; Lago-Peñas et al., 2010; Liu et al., 2015b; Nassis et al., 2015; Rampinini et al., 2009). Moreover, technical performance profiles can be improved when contextualized by team quality (Liu et al., 2015b; Rampinini et al., 2009). However, there is still a lack of studies comparing the technical performance of teams of differing quality. Consequently, the present study investigates which technical metrics differ between higher- and lower-ranked teams and identifies the indicators most strongly associated with match success in both groups.

Situational variables like the quality of opposition, match status, and match location have also been shown to influence team performance (Lago, 2009; Taylor et al., 2008). While all three have been extensively studied, match location can be further explored. According to Tucker et al. (2005), match location can affect primary, secondary, and tertiary measures. "*Primary measures consisted of fundamental skill execution (i.e., batting average, free throw percentage, penalties per game). Secondary measures usually reflected the scoring necessary to win a contest (e.g., points or goals scored), while tertiary measures indicated the final match outcome (win/loss, point's difference etc.)*" (p. 23). Most studies regarding match location have evaluated its impact through tertiary measures (e.g., Allen & Jones, 2012; Almeida & Volossovitch, 2017; Goumas, 2014; Leite, 2017; Liu et al., 2016; Peeters & van Ours, 2021; Schwartz & Barsky, 1977), consistently reporting higher success rates at home compared to away, a phenomenon known as "*home advantage*."

A limited number of studies have examined the impact of match location on primary measures, in the form of technical performance metrics (e.g., Carmichael & Thomas, 2005; Liu et al., 2015c; Lago-Peñas & Lago-Ballesteros, 2011; Taylor et al., 2008; Tucker et al., 2005), and even fewer have accounted for team quality in this context (Lago-Peñas & Lago-Ballesteros, 2011; Liu et al., 2015c). Lago-Peñas & Lago-Ballesteros (2011) and Liu et al. (2015c) suggest that stronger and weaker teams do not experience the same home advantage. Thus, it seems important to examine how match location affects technical performance, while considering how team quality may moderate these effects.

A range of technical performance metrics were selected according to existing literature (Castellano et al., 2012; Lago-Ballesteros & Lago-Peñas, 2010; Lago-Peñas et al., 2010; Lago-Peñas & Lago-Ballesteros, 2011; Liu et al., 2015a; Liu et al., 2016; Mao et al., 2016). A key contribution of this study is the introduction of four metrics that have been largely unexplored in similar analyses: Tackle Defensive 3rd, Tackle Attacking 3rd, Long Pass Completed % and Shot Distance. While tackles themselves have been incorporated in previous analyses (Almeida et al., 2014; Kubayi & Larkin, 2020; Liu et al., 2015a; Liu et al., 2015b; Liu et al., 2015c; Liu et al., 2016; Mao et al., 2016; Stafylidis et al., 2024; Tucker et al., 2005), no attention has been paid to their location on the pitch. By differentiating tackles in the defensive and attacking thirds of the pitch, this study offers a more nuanced look at their tactical significance. Long Pass Completed % can indicate a "*direct*" playing style driven by frequent long passes (Fernández-Navarro et al., 2018; González-Rodenas et al., 2020a), while Shot Distance provides insights into shot quality, given the role of shooting distance in scoring likelihood (González-Rodenas et al., 2020b; Pollard et al., 2004).

Previous studies have classified teams based on final league rankings, often without applying a rigorous statistical framework (Lago-Ballesteros & Lago-Peñas, 2010; Liu et al., 2015b; Rampini et al., 2009). To address this gap, this study employs k-means clustering to objectively categorize the 20 teams at the end of the season, focusing on the top and bottom clusters for subsequent analysis.

Accordingly, the present study aims to: (1) compare technical performance metrics between top- and bottom-tier English Premier League teams; (2) identify which technical metrics are affected by match location; and (3) determine the key performance indicators most strongly associated with winning.

MATERIAL AND METHODS

Data

The sample contained 18 technical performance metrics of teams in the 2023–24 English Premier League season. Match statistics were collected from the publicly available Sports Reference's FBref (FBref.com, 2024), which is powered by Opta Sports, a data collection company considered to be the gold standard (Sapp et al., 2017).

Initially, k-means clustering was applied to divide the 20 teams into four clusters (see Section 2.2 for more details). Teams that finished 1st to 3rd were assigned to the "*top*" tier, while those ranked 17th to 20th formed the "*bottom*" tier. This selection resulted in 114 match observations in the top group, and 152 observations in the bottom group.

Of the 18 metrics, 16 were directly obtained from FBref (Fbref.com, 2024) and checked for multicollinearity ($\mathrm{r} > 0.8$). The remaining two metrics were derived from the existing metrics: Long Pass Completed %, calculated as $\frac{\text{Long Pass Completed}}{\text{Pass Completed}} \times 100$, and Shooting Accuracy %, calculated as $\frac{\text{Shot on Target}}{\text{Shot}} \times 100$. Operational definitions for all metrics (Table 1) are based on FBref (FBref.com, 2024) and other sources (Liu et al., 2013; Liu et al., 2015a).

Statistical analysis

K-means clustering was applied to group the 20 teams according to final league points in the 2023–24 Premier League season. The elbow method, as shown in Figure 1, indicated that the optimal number of clusters was four, after which the top cluster (1st–3rd) and bottom cluster (17th–20th) were selected for further analysis.

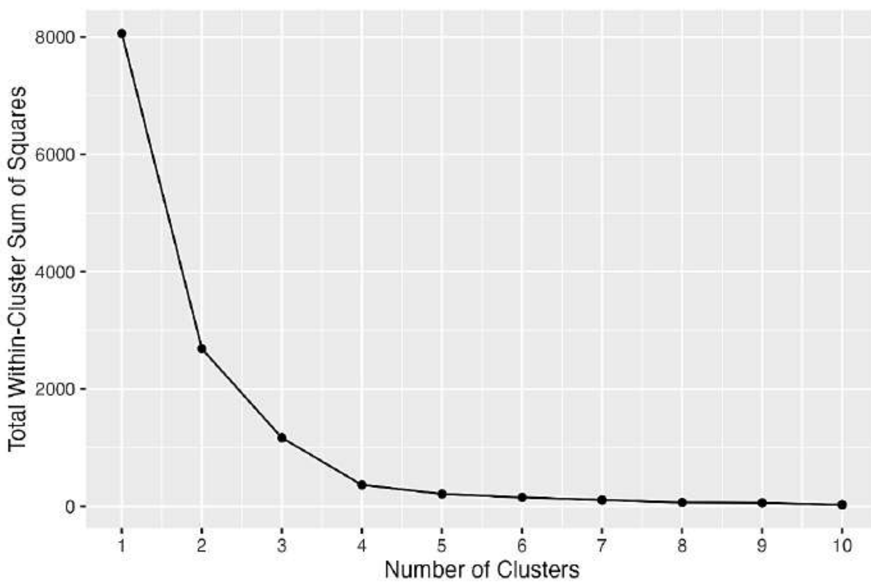

Figure 1. Elbow method for determining the optimal number of clusters.

Descriptive data of the metrics were presented using means (M) and standard deviations (SD) according to tier (top-tier and bottom-tier) and match location (home and away). The assumptions of normality of residuals was assessed through Shapiro–Wilk's test and homogeneity of variances was evaluated using Levene's test. As most of the metrics did not satisfy these assumptions, Mann–Whitney U tests, which are statistically equivalent to the Wilcoxon Rank–Sum test, were performed instead of Student's t-tests. First, a Mann–Whitney U test was carried out to analyse the differences in technical metrics between top- and bottom-tier teams. Then, the same test was implemented again to find the differences in metrics between home and away matches in both tiers. Rank-based effect sizes (ES) were calculated for each Mann–Whitney U test and interpreted as small (ES = 0.1), medium (ES = 0.3), or large (ES = 0.5) (Cohen, 1988).

Following this, binary logistic regression was conducted for both tiers to identify the statistically significant performance indicators associated with winning. Match outcome was the dependent variable (1 = wins and 0 = draws and losses), while the values of the performance indicators were the independent variables, which were modelled to calculate the logarithm of odds of winning a match (Peng et al., 2002). Long Pass Completed % and Shooting Accuracy % were excluded in the regression due to issues with multicollinearity ($r > 0.8$). Although the dataset was unbalanced, as top-tier teams had a higher proportion of wins and bottom-tier teams had a higher proportion of draws and losses, no under sampling or oversampling methods were utilized. Crone and Finlay (2012) argue that such balancing does not improve logistic models and that retaining all data yields better results. Model fit was evaluated using the Hosmer–Lemeshow goodness-of-fit test, and Nagelkerke R^2 was calculated to measure the model's explanatory strength. All statistical analyses were carried out using the statistical software R (R Core Team, 2024), with $p < .05$ considered statistically significant.

Table 1. Operational definitions of the technical performance metrics.

Offensive Metrics	
Shot	An attempt to score a goal, made with any (legal) part of the body, either on or off target.
Shot on Target	An attempt to goal which required intervention to stop it going in or resulted in a goal/shot which would go in without being diverted.
Shooting Accuracy %	Shot on Target as a proportion of Shot.
Shot Distance	Average distance, in yards, from goal of all shots taken. Only players with a minimum of 0.395 shots per squad game are included in this statistic. Penalty kicks are excluded.
Successful Take-On	An attempt by a player to beat an opponent when they have possession of the ball. A successful take-on means the player beats the defender while retaining possession.
Defensive Metrics	
Shot on Target Against	A conceded attempt on goal which required intervention to stop it going in or resulted in a goal/shot which would go in without being diverted.
Tackle Defensive 3rd	The act of gaining possession from an opposition player, when he is in possession of the ball in the defensive third of the pitch.
Tackle Attacking 3rd	The act of gaining possession from an opposition player, when he is in possession of the ball in the attacking third of the pitch.
Blocked Shot	A defensive block, blocking a shot going on target. This must be awarded to the player who blocks the shot.
Clearance	Players attempt to get the ball out of the danger zone, when there is pressure behind them, or there is pressure on the player to clear the ball from the danger zone.
Yellow Card	Where a player was shown a yellow card by the referee for reasons of foul, persistent infringement, hand ball, dangerous play, time wasting, etc.
Passing & Organizing Metrics	
Pass Completed	An intentional ball from one player to another.
Long Passes Completed	A completed pass longer than 30 yards.
Through Ball	A completed pass sent between defenders back into open space.
Cross	Any ball sent into the opposition team's area from a wide position.
Offside	Being caught in an offside position resulting in a free kick to the opposing team.
Aerial Duel Won	Two players competing for a ball in the air, for it to be an aerial both players must jump and challenge each other in the air and have both feet off the ground. The player who wins the duel gets the Aerial Won.
Long Pass Completed %	Long Pass Completed as a proportion of Pass Completed.

RESULTS

Table 2 presents the results of the Mann–Whitney U test comparing the technical performance of top- and bottom-tier teams. For offensive metrics, top-tier teams recorded significantly more total shots (p = .00, ES = 0.53, large effect), on-target shots (p = .00, ES = 0.47, moderate effect) and successful take-ons (p = .03, ES = 0.13, small effect). By contrast, shooting accuracy (p = .07, ES = 0.11, small effect) and average shot distance (p = .10, ES = 0.10, small effect) did not reach statistical significance at the p < .05 level.

Regarding defensive metrics, bottom-tier teams conceded a higher number of on-target shots (p = .00, ES = 0.52, large effect) and recorded more clearances (p = .00, ES = 0.54, large effect) and blocked shots (p = .00, ES = 0.39, moderate effect). They also made more tackles in the defensive third of the pitch (p = .00, ES = 0.39, moderate effect) and received more yellow cards (p = .00, ES = 0.19, small effect). In contrast, top-tier teams attempted more tackles in the attacking third of the pitch (p = .00, ES = 0.22, small effect).

For passing and organizing metrics, top-tier teams completed more passes (p = .00, ES = 0.74, large effect), through balls (p = .00, ES = 0.48, moderate effect), long passes (p = .00, ES = 0.29, small effect), and crosses (p = .00, ES = 0.19, small effect). Bottom-tier teams, on the other hand, relied more heavily on long passes relative to their total passes (p = .00, ES = 0.62, large effect) and won more aerial duels (p = .00, ES = 0.27, small effect). No significant differences were found concerning the number of offsides per match (p = .62, ES = 0.03).

Table 2. Comparison of technical performance metrics between top- and bottom-tier teams.

Metric	Top-Tier Teams (M ± SD)	Bottom-Tier Teams (M ± SD)	Z	*p*	Effect Size (ES)
Metrics Relating to Offense					
Shot	18.52 ± 7.11	10.97 ± 4.61	8.60	.00*	0.53
Shot on Target	6.46 ± 3.23	3.49 ± 2.09	7.69	.00*	0.47
Successful Take-On	8.69 ± 3.49	7.76 ± 3.72	2.19	.03*	0.13
Shooting Accuracy %	36.00 ± 15.00	32.00 ± 16.00	1.82	.07	0.11
Shot Distance	16.61 ± 2.07	17.24 ± 3.64	-1.65	.10	0.10
Metrics Relating to Defence					
Shot on Target Against	2.97 ± 1.94	5.88 ± 2.90	-8.44	.00*	0.52
Clearance	13.64 ± 6.44	24.76 ± 10.37	-8.78	.00*	0.54
Blocked Shot	2.54 ± 2.10	4.61 ± 2.75	-6.41	.00*	0.39
Tackle Defensive 3rd	6.26 ± 3.36	9.37 ± 4.09	-6.29	.00*	0.39
Tackle Attacking 3rd	2.92 ± 1.83	2.13 ± 1.77	3.58	.00*	0.22
Yellow Card	1.63 ± 1.33	2.18 ± 1.48	-3.08	.00*	0.19
Metrics Relating to Passing and Organizing					
Pass Completed	562.16 ± 132.16	305.12 ± 105.26	12.07	.00*	0.74
Long Pass Completed %	7.20 ± 2.20	11.30 ± 3.36	-10.12	.00*	0.62
Through Ball	2.55 ± 1.74	0.98 ± 1.18	7.81	.00*	0.48
Long Pass Completed	39.18 ± 11.82	32.36 ± 8.85	4.81	.00*	0.29
Aerial Duel Won	12.38 ± 6.38	15.55 ± 6.17	-4.35	.00*	0.27
Cross	19.18 ± 8.63	15.88 ± 8.21	3.14	.00*	0.19
Offside	2.01 ± 1.72	1.87 ± 1.63	0.00	.62	0.03

Note. * = Significant at $p < .05$

Table 3. Differences in technical performance metrics for top-tier teams by match location.

Metric	Home (M ± SD)	Away (M ± SD)	Z	*p*	Effect Size (ES)
Metrics Relating to Offense					
Shot	20.88 ± 7.10	16.16 ± 6.33	-3.51	.00*	0.33
Shot on Target	7.12 ± 3.11	5.79 ± 3.23	-2.11	.03*	0.20
Shooting Accuracy %	35 ± 12	36 ± 17	0.72	.47	0.07
Successful Take-On	8.95 ± 3.77	8.44 ± 3.20	0.00	.66	0.04
Shot Distance	16.67 ± 2.00	16.55 ± 2.15	0.00	.95	0.01
Metrics Relating to Defence					
Clearance	11.40 ± 5.42	15.88 ± 6.63	3.73	.00*	0.35
Blocked Shot	1.88 ± 1.60	3.19 ± 2.33	3.16	.00*	0.30
Tackle Defensive 3rd	5.44 ± 3.15	7.09 ± 3.39	2.68	.01*	0.25
Tackle Attacking 3rd	3.23 ± 1.93	2.61 ± 1.69	-1.67	.09	0.16
Yellow Card	1.47 ± 1.36	1.79 ± 1.29	1.58	.11	0.15
Shot on Target Against	2.67 ± 1.50	3.28 ± 2.27	0.00	.29	0.10
Metrics Relating to Passing and Organizing					
Cross	21.02 ± 9.32	17.35 ± 7.52	-2.13	.03*	0.20
Offside	2.21 ± 1.71	1.81 ± 1.73	-1.58	.11	0.15
Pass Completed	583.54 ± 124.95	540.77 ± 136.76	-1.56	.12	0.15
Long Pass Completed %	7.01 ± 2.19	7.38 ± 2.22	1.09	.27	0.10
Aerial Duel Won	12.75 ± 5.75	12.00 ± 6.98	-1.04	.30	0.10
Long Pass Completed	40.02 ± 12.46	38.35 ± 11.18	-0.64	.52	0.06
Through Ball	2.63 ± 1.80	2.47 ± 1.68	0.00	.68	0.04

Note. * = Significant at $p < .05$

As shown in Table 3, when playing at home, top-tier teams took significantly more total (p = .00, ES = 0.33, moderate effect) and on-target (p = .03, ES = 0.20, small effect) shots, along with more crosses (p = .03, ES = 0.20, small effect). In away matches, these teams made more clearances (p = .00, ES = 0.35, moderate effect) and blocked shots (p = .00, ES = 0.30, moderate effect). They also made more tackles in the defensive third (p = .01, ES = 0.25, small effect).

Table 4. Differences in technical performance metrics for bottom-tier teams by match location.

Metric	Home (M ± SD)	Away (M ± SD)	Z	*p*	Effect Size (ES)
Metrics Relating to Offense					
Shot	12.75 ± 4.83	9.18 ± 3.62	-4.52	.00*	0.37
Successful Take-On	8.26 ± 3.63	7.25 ± 3.76	-2.16	.03*	0.18
Shooting Accuracy %	30.00 ± 15.00	35.00 ± 17.00	2.15	.03*	0.17
Shot on Target	3.74 ± 2.26	3.25 ± 1.89	-1.35	.18	0.11
Shot Distance	17.19 ± 3.02	17.29 ± 4.19	0.00	.95	0.01
Metrics Relating to Defence					
Blocked Shot	3.87 ± 2.64	5.34 ± 2.68	3.42	.00*	0.28
Tackle Attacking 3rd	2.59 ± 1.83	1.67 ± 1.59	-3.37	.00*	0.27
Clearance	22.66 ± 10.92	26.86 ± 9.41	2.56	.01*	0.21
Tackle Defensive 3rd	8.82 ± 4.17	9.92 ± 3.96	1.73	.08	0.14
Yellow Card	1.97 ± 1.35	2.38 ± 1.59	0.00	.10	0.13
Shot on Target Against	5.54 ± 2.84	6.21 ± 2.94	1.55	.12	0.13
Metrics Relating to Passing and Organizing					
Cross	18.75 ± 9.11	13.01 ± 6.01	-3.99	.00*	0.32
Long Pass Completed	33.86 ± 9.01	30.87 ± 8.49	-2.25	.02*	0.18
Pass Completed	324.39 ± 115.24	285.86 ± 90.95	-1.88	.06	0.15
Offside	2.08 ± 1.90	1.66 ± 1.28	-0.87	.39	0.07
Aerial Duel Won	15.87 ± 6.54	15.24 ± 5.80	0.00	.78	0.02
Through Ball	1.00 ± 1.23	0.96 ± 1.14	0.00	.88	0.01
Long Pass Completed %	11.15 ± 3.16	11.44 ± 3.57	0.03	.97	0.00

Note. * = Significant at $p < .05$

Table 4 presents the technical performance metrics of bottom-tier teams according to match location. At home, these teams attempted significantly more total shots (p = .00, ES = 0.37, moderate effect) and had a higher number of successful take-ons (p = .03, ES = 0.18, small effect). They also performed more tackles in the attacking third (p = .00, ES = 0.27, small effect), along with more crosses (p = .00, ES = 0.32, moderate effect) and long passes (p = .02, ES = 0.18, small effect). In away games, bottom-tier teams displayed better shooting accuracy (p = .03, ES = 0.17, small effect). Additionally, they blocked more shots (p = .00, ES = 0.28, small effect) and completed more clearances (p = .01, ES = 0.21, small effect).

Table 5. Binary logistic regression results for top-tier teams.

Variable	B	Odds Ratio (OR)	*p*	Lower 95% CI	Upper 95% CI
Cross	-0.36	0.70	.00*	0.57	0.86
Aerial Duel Won	0.31	1.37	.00*	1.10	1.69
Shot on Target	0.50	1.65	.01*	1.12	2.42
Shot on Target Against	-0.61	0.55	.01*	0.34	0.88
Tackle Attacking 3rd	-0.57	0.57	.02*	0.35	0.93
(Intercept)			.03		
Through Ball	-0.32	0.73	.16	0.47	1.13
Blocked Shot	-0.33	0.72	.17	0.45	1.15
Clearance	-0.11	0.90	.20	0.77	1.06
Yellow Card	-0.46	0.63	.20	0.31	1.28
Shot Distance	-0.20	0.82	.27	0.57	1.17
Tackle Defensive 3rd	-0.08	0.93	.60	0.69	1.24
Successful Take-On	-0.05	0.95	.66	0.75	1.20
Pass Completed	0.00	1.00	.73	0.99	1.01
Long Pass Completed	0.01	1.01	.74	0.94	1.09
Shot	0.03	1.03	.80	0.82	1.29
Offside	-0.05	0.95	.81	0.63	1.44

Note. * = Significant at $p < .05$

Table 5 presents the binary logistic regression results for top-tier teams, indicating five significant metrics: Aerial Duel Won, Shot on Target, Cross, Tackle Attacking 3rd, and Shot on Target Against. Each additional Aerial Duel Won (*p* = .00) and Shot on Target (*p* = .01) increased the odds of winning in a game by 37% and 65%, respectively. On the other hand, per increase for Cross (*p* = .00), Tackle Attacking 3rd (*p* = .02), and Shot on Target Against (*p* = .01), the odds of winning decreased by 30%, 45%, and 43%, respectively. The Hosmer-Lemeshow goodness-of-fit test returned a nonsignificant *p*-value of .46, and Nagelkerke R^2 was .71.

Table 6. Binary logistic regression results for bottom-tier teams.

Variable	B	Odds Ratio (OR)	*p*	Lower 95% CI	Upper 95% CI
Shot on Target Against	-0.46	0.63	.00*	0.48	0.84
Clearance	0.12	1.13	.01*	1.03	1.23
Shot	0.19	1.21	.10	0.96	1.52
Pass Completed	-0.01	0.99	.13	0.98	1.00
Through Ball	0.36	1.43	.16	0.87	2.36
Successful Take-Ons	-0.12	0.89	.20	0.74	1.07
Cross	-0.08	0.93	.22	0.82	1.05
Long Pass Completed	0.06	1.06	.22	0.97	1.16
Blocked Shot	-0.17	0.84	.27	0.62	1.14
Shot on Target	0.19	1.21	.31	0.84	1.76
Shot Distance	0.10	1.10	.32	0.91	1.33
Tackle Defensive 3rd	-0.09	0.92	.34	0.77	1.09
Yellow Card	-0.20	0.82	.36	0.53	1.26
Aerial Duel Won	-0.05	0.95	.37	0.86	1.06
(Intercept)			.45		
Offside	0.13	1.14	.52	0.77	1.70
Tackle Attacking 3rd	-0.06	0.94	.77	0.63	1.42

Note. * = Significant at p < .05

As seen in Table 6, the binary logistic regression of bottom-tier teams revealed only two significant metrics: Clearance and Shot on Target Against. Per increase in a game, Clearance (*p* = .01) increased winning odds by 13%, while Shot on Target Against (*p* = .00) decreased them by 37%. The Hosmer-Lemeshow goodness-of-fit test returned a non-significant *p*-value of .16, and Nagelkerke R^2 had a value of .47.

DISCUSSION

The objective of this study was threefold: (1) to compare the technical performance of top- and bottom-tier teams in the 2023–24 English Premier League season; (2) to identify the technical metrics affected by match location; and (3) to determine the statistically significant performance indicators associated with winning. K-means clustering, Mann–Whitney U tests, and binary logistic regression were implemented in the analyses.

Regarding the first aim, the results showed that top-tier teams had a higher number of total and on-target shots, as well as for the number of successful take-ons. Previous studies have also found similar findings (Andrzejewski et al., 2022; González-Rodenas et al., 2015; Lago-Ballesteros & Lago-Peñas, 2010; Liu et al., 2015b; Liu et al., 2015c; Liu et al., 2016; Souza et al., 2019). However, Shot Distance and Shooting Accuracy % did not display statistically significant differences between the tiers. Considering the importance of the distance of a shot on scoring, and thus shot quality, (González-Rodenas et al., 2020b; Pollard et al., 2004) the lack of significance for Shot Distance may have contributed to the similar result in Shooting Accuracy %, which measures the average quality of shots in a game. Collectively, these findings indicate that the quantity of shots (Shot) better differentiates the top and bottom tiers than average shot quality (Shooting Accuracy %). In line with this claim, research conducted on the 2008–09 season of the Spanish La Liga reported significant differences between top, middle, and bottom teams for the number of total shots, but not for shooting accuracy (Lago-Ballesteros & Lago-Peñas, 2010).

Defensively, bottom-tier teams conceded a greater number of shots on target, consistent with past research (Andrzejewski et al., 2022; Delgado Bordonau et al., 2013; Souza et al., 2019). Moreover, they made a higher frequency of clearances, blocked shots, and tackles in the defensive third of the pitch. These teams also received more yellow cards, in accordance with the negative correlation between disciplinary counts and league position (Sapp et al., 2017). Meanwhile, among top-tier teams, the only defensive metric they had significantly higher values been the number of tackles in the attacking third. Previous studies have established that such tackling in advanced areas of the pitch are intended to gain possession closer to the opponent's goal, further linking this to offensive success (Almeida et al., 2014; Fernández-Navarro et al., 2016; González-Rodenas et al., 2020c; T, 2019; Liu et al., 2016).

Taking into consideration the metrics related to passing and organizing, top-tier teams completed nearly twice as many total passes, along with more through balls and long passes. Some of these findings are supported by other studies (Andrzejewski et al., 2022; Liu et al., 2015b; Liu et al., 2015c; Liu et al., 2016). Although crossing has been negatively associated with win rates during the 2012–13 La Liga season (Liu et al., 2016), the present study showed that top-tier teams attempted more crosses. This contrast in results may suggest changing tactical strategies or may simply stem from league-specific characteristics. The current investigation also demonstrated a more direct style of play for bottom-tier teams, as they relied on a greater proportion of long passes relative to their total passing. According to Liu et al. (2016), teams that won more aerial duels tended to win more games over the 2012–13 La Liga season, attributing this to the control of attacking and defensive phases in a match this advantage provides. Therefore, the fact that, in the present study, bottom-tier teams won more aerial duels than top-tier teams is of considerable interest. A plausible explanation for this inconsistency is that in the context of the 2023–24 English Premier League season, bottom-tier teams placed extra emphasis on aerial training due to their heavy reliance on long balls, thereby enhancing aerial ability despite their lower ranking.

With respect to the second objective, in both tiers, home matches were associated with greater offensive outputs, particularly in shots and crosses. Similar findings have been made in past studies (Carmichael & Thomas, 2005; Fernández-Navarro et al., 2018; Gómez et al., 2018; González-Rodenas et al., 2015; González-Rodenas et al., 2020c; Lago-Peñas & Lago-Ballesteros, 2011; Tucker et al., 2005). Expanding on this, top-tier teams produced additional on-target attempts, while bottom-tier teams completed more successful take-ons and long passes (Carmichael & Thomas, 2005; Lago-Peñas & Lago-Ballesteros, 2011; Tucker et al., 2005).

By contrast, away matches impacted primarily defensive actions, prompting more clearances, blocked shots, and tackles (Carmichael & Thomas, 2005; Lago-Peñas & Lago-Ballesteros, 2011; Tucker et al., 2005). The specific location of these tackles differed between the tiers, however: top-tier teams tackled more in the defensive third, whereas the bottom tier showed an increased number of attacking-third tackles. Further investigation can examine why this may be the case. Interestingly, bottom-tier teams had better shooting accuracy away from home, yet no past studies have made similar findings—likely because shooting accuracy has not been studied in relation to match location. As such, future research should incorporate this metric to determine if this trend holds true in other contexts.

The impact of match location on disciplinary consequences has remained inconclusive in existing literature. While some note a greater number of yellow cards for away sides (Carmichael & Thomas, 2005; Lago-Peñas

& Lago-Ballesteros, 2011; Sapp et al., 2017; Thomas et al., 2006), others find no significant differences (Tucker et al., 2005). In the present study, the location of a match did not significantly affect the number of yellow cards received, but this should be interpreted with caution due to the exclusion of mid-table teams in the analysis.

These findings also support the conclusions of Lago-Peñas & Lago-Ballesteros (2011) and Liu et al. (2015c), both of whom indicated that stronger and weaker teams did not experience the same home advantage. In the present study, top-tier teams recorded higher values in Shot, Shot on Target, and Cross at home, while bottom-tier teams had higher totals for Shot, Successful Take-On, Cross, and Long Pass Completed. The greater number of significantly different metrics between home and away matches for bottom-tier teams aligns particularly well with Liu et al. (2015c), who reported that stronger teams tend to maintain more consistent technical performance across match location.

For the final objective, binary logistic regression was conducted to determine the metrics that had a statistically significant impact on winning. Among top-tier teams, Aerial Duel Won and Shot on Target were identified to be the significant positive predictors. Per increase in these metrics, the odds of winning increased by 37% and 65%, respectively, per event. The association between aerial duels and winning a match coincides with previous studies (Liu et al., 2015a), though the result in the present study is particularly noteworthy as the Mann–Whitney U test revealed that top-tier teams were less dominant in the air compared to bottom-tier teams. Therefore, it is recommended that coaches of top-tier teams improve their team's aerial ability by implementing more heading exercises to maximize the chances of winning. The pronounced effect of Shot on Target has also been reported in past studies (Bilek & Ulas, 2019; Castellano et al., 2012; Lago-Peñas et al., 2010; Liu et al., 2015a; Liu et al., 2016; Mao et al., 2016; Stafylidis et al., 2024). However, Shot did not significantly affect winning, reinforcing the notion that creating a shot with high quality (Shot on Target) matters more than the sheer overall quantity of shots (Shot) in generating favourable results (Liu et al., 2015a; Liu et al., 2016; Yue et al., 2014).

In the same model, Cross, Tackle Attacking 3rd, and Shot on Target Against appeared as negative predictors, reducing the odds of winning by 30%, 43%, and 45%, respectively, per increase in metric. Previous studies have similarly observed the detrimental effect of crossing, noting its unpredictability and risk of conceding counterattacks (Fernández-Navarro et al., 2016; Lago-Peñas et al., 2010; Liu et al., 2015a; Liu et al., 2016). The substantial negative effect of Tackle Attacking 3rd is surprising given previous claims that acquiring possession in advanced areas of the pitch—for example, through tackling—is advantageous despite the risks of fouls (Almeida et al., 2014; Fernández-Navarro et al., 2016; González-Rodenas et al., 2020c; Jamil, 2019; Liu et al., 2016). However, the findings of the present study suggest that, for top-tier teams, the risks involved in tackling in the attacking third outweighed its benefits. The result of Shot on Target Against is consistent with past research (Castellano et al., 2012), underscoring the critical need to limit high-quality shooting opportunities for opponents.

Among bottom-tier teams, Clearance was the only significant positive factor, raising winning odds by 12% per instance. This performance metric was not significant in the regression for top-tier teams, highlighting the importance of effective ball clearing for weaker sides, who often face stronger opposition (Bilek & Ulas, 2019). Again, Shot on Target Against was identified as a significant negative predictor, reducing the odds of winning by 37% per increase in metric. This was the only variable to achieve statistical significance in both models, emphasizing its pivotal influence on match success regardless of team quality.

CONCLUSION

In summary, this study identified significant differences in technical performance between top- and bottom-tier teams, highlighted the influence of match location, and uncovered the key performance indicators significantly associated with winning. Future research can continue to incorporate the newly explored metrics—Tackle Defensive 3rd, Tackle Attacking 3rd, Long Pass Completed % and Shot Distance—in a similar context to enhance the understanding of team performance in football.

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The author declares that the study complies with the current laws of the Republic of Korea.

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ORIGINAL ARTICLE

The effects of polarized training on time trial performance in trained and highly-trained triathletes

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ABSTRACT

The polarized training model (POL), with its unique training intensity distribution (TID), emerges as an effective alternative to improve time trial performance. This study aimed to evaluate the effects of 13 weeks of training by applying a POL model in trained and highly-trained triathletes, using a percentage of TID of 75/0/25 in zones 1, 2, and 3, respectively. To analyse training effects, the assessment was performed at the beginning and the end of the study on time trials: 200m swimming (T200m), 4 minutes (T4min) and 20 minutes (T20min) cycling, and 6 minutes (T6min) running. Analysis of covariance (ANCOVA), supplemented with post hoc tests, revealed that POL training did not produce significant changes: T200m (pre = 3.03 ± 0.58, post = 2.90 ± 0.53, p = .59), T4min (pre = 272.09 ± 55.91, post = 290 ± 69.33, p = .50), T20min (pre = 204.91 ± 51.3, post = 216.36 ± 56.6, p = .62) and T6min (pre = 15.71 ± 1.69, post = 15.86 ± 1.54, p = .82). Even though training time in Z1 and Z3 is relevant, our results suggest that optimal programs for trained and highly trained triathletes should not exclude training in Z2. Furthermore, to optimize the effects of the POL model, it is essential to consider the athlete's initial level of performance and the duration of the program.

Keywords: Performance analysis, Performance framework, Training intensity distribution, Overtraining, Physiological capacity.

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INTRODUCTION

In endurance sports, time-trial performance tests are considered one of the most effective methods of evaluating the effects of a training program. In addition, they allow the classification of the athlete's performance level in a sensitive and accessible form without using mathematical models or access to a laboratory (Valenzuela et al., 2021). These tests are characterized by the assessment of the athlete's ability to maintain maximum power or speed for a given period of time (Dolci et al., 2020), which makes it possible to establish a direct relationship between the physiological adaptations induced by training and performance in a specific sport discipline(Cerezuela-Espejo et al., 2018).

The polarized (POL) model has emerged as a highly effective alternative for the improvement and refinement of this type of testing (Rosenblat et al., 2019). This strategy, with its exclusive training intensity distribution (TID), is traditionally characterized by accumulating ∼75-80 % of training volume in the low intensity zone (Z1), ∼0-5 % in the moderate-intensity zone (Z2), and the remaining ∼15-20 % in the high-intensity zone (Z3) (i.e., Z1>Z3>Z2) (Treff et al., 2019). In this regard, recent studies have demonstrated that POL training has positive effects on modifying physiological responses related to performance enhancement in several elite athletes, including rowers (Treff et al., 2017), runners (Ingham et al., 2012), swimmers (Pla et al., 2019) and cyclists (Schneeweiss et al., 2022). Furthermore, research on the annual distribution employed by top world-class endurance athletes has indicated a tendency to utilize POL models (Casado et al., 2022; Seiler, 2010).

Several hypotheses have been proposed to elucidate the physiological mechanisms responsible for the effectiveness of the POL model in enhancing performance in endurance athletes. One of these is highlighted by the enhancement of mitochondrial capacity, and involves two signalling pathways that converge on the expression of peroxisome proliferator-activated receptor gamma coactivator 1 alpha (PGC-1α) (Casado et al., 2023). The first pathway is based on mitochondrial protein synthesis through calcium signalling and is related to low-intensity training at Z1, stimulated by high-volume steady-state sessions (Bishop et al., 2019). The second pathway is activated by an increase in the intramuscular ATP:ADP/AMP ratio and cellular energy depletion, leading to an accumulation of reactive molecules and energy intermediates that activate 5'-adenosine monophosphate-activated protein kinase (AMPK). Activation of this protein stimulates PGC-1α and thus generates mitochondrial biogenesis (Gibala et al., 2012). This signalling pathway is induced by Z3 training, which is carried out through intervallic sessions at intensities above the individual anaerobic threshold (IAT) or close to maximal oxygen uptake (VO2max) (van der Zwaard et al., 2021). However, a high volume of allocated training time in Z3 has been associated with negative cardiovascular, hormonal and metabolic consequences, as well as a decrease in performance (Bellinger, 2020). For this reason, to balance the positive and negative effects of high-intensity training, endurance athletes should consider combining Z3-regulated sessions with high volumes of Z1 training in order to optimize mitochondrial adaptations, physiological capacity and time trail and competition performance (Foster et al., 2022; van der Zwaard et al., 2021).

Despite the physiological mechanisms that explain the beneficial effects of POL model, there are significant inconsistencies and limitations in the evidence supporting the notion that this method is optimal (Burnley et al., 2022). This is particularly evident in lower-level endurance athletes (Silva Oliveira et al., 2024). In this sense, two recent studies conducted with trained endurance athletes (Festa et al., 2019; Röhrken et al., 2020) failed to demonstrate superior physiological adaptations and time trial performance improvements when comparing the effect of POL training with other TID models (pyramidal [PYR] and threshold [THR], respectively). Furthermore, a longitudinal case study of an elite trail runner (Rivera-Kofler et al., 2024) found that the greatest physiological changes were reported during the period when the athlete increased training volume in the Z2 (i.e., moderate intensity zone), which increased the internal training load with the measures of total training impulse (TRIMPs) and consequently improved the athlete's physiological capacity. However, the training volume reported in this study was significantly lower than that used by elite and world-class endurance runners (Casado et al., 2022; Haugen et al., 2022). It is important to note that such adaptations appear more common in trained and highly trained athletes, who have less time for long training days and must compensate for this lack of volume with regulated sessions in the moderate intensity zone (Z2). However, this tendency may lead to reduced adaptation as neither calcium-dependent nor AMPK pathways are likely sufficiently stimulated to increase mitochondrial capacity(Foster et al., 2022).

For this reason, although the POL model has been extensively validated in elite and world-class endurance athletes, its effectiveness in improving time trial performance, especially considering different performance levels, still needs to be explored. Therefore, this study aimed to evaluate the effects of 13 weeks of training by applying a POL model in trained and highly-trained triathletes, using a percentage of TID of 75/0/25 in zones 1, 2, and 3, respectively.

METHODS

Participants

Exclusion criteria were established for athletes who missed more than three training sessions per week or whose total training volume was less than 80% of the total training load. A total of 23 triathletes from Viña del Mar, Chile, participated in the study; 10 participants were excluded from the intervention due to health problems or other personal reasons. Their main goal for the season was to prepare for an Ironman 70.3 distance triathlon scheduled for 17 November 2024 in Valdivia, Chile. According to a 6-tiered classification framework that takes into account training volume and performance variables (McKay et al., 2022), all participants were classified into performance tiers 2 and 3, corresponding to trained/development and highly trained/national level athletes, respectively. Before the intervention, all subjects had been training consistently for >2 years (average experience 3.9 ± 2.2 years), with an average training volume of 10 h 30min ± 1 h 20 min per week, divided between swimming, cycling, and running. At the start of the study, the athletes were in the final phase of their overall seasonal preparation, characterized by a training volume predominantly in Z1.

Table 1. General characteristics of the participants before the study.

Characteristics of athletes	Total	Women (n = 4)	Men (n = 9)	*p*-value
Age (y)	32.08 ± 6.48	31.25 ± 3.5	32.44 ± 7.61	.77
Weight (kg)	66.42 ± 10.54	56.38 ± 11.95	70.89 ± 6.35	.01
Height (cm)	167.54 ± 7.07	160.50 ± 4.12	170.67 ± 5.74	.09
Body mass Index (kg/m^2)	23.57 ± 3.04	21.70 ± 3.45	24.40 ± 2.63	.14
VO_{2max} (mL/min/kg)	57.38 ± 5.87	54.85 ± 6.94	58.50 ± 5.387	.32
HRmax (bmp)	191.23 ± 8.26	190.25 ± 6.02	191.67 ± 9.39	.78
Bike 20 min. best (W/kg)	3.33 ± 0.97	2.75 ± 0.95	3.59 ± 0.91	.15
Run 10 km best (min)	44.38 ± 6.74	49.25 ± 7.45	42.22 ± 5.49	.08
Triathlon training experience (Years)	3.92 ± 2.21	2.50 ± 0.57	4.56 ± 2.40	

This intervention study is a randomized, controlled trial in which athletes were randomly assigned to a common training group that followed a POL intensity distribution trend for 13 weeks. Performance tests were assessed at baseline and post-intervention. Data confidentiality was ensured through the coding of participants' names, data were stored in the research computer with the principal investigator's login code. The research was conducted following the recommendations of the Helsinki declaration for human studies (World Medical Association, 2013).

Performance test and training intensity distribution

The performance tests and training intensity distribution for the three disciplines were presented based on the triphasic model (Skinner & Mclellan, 1980) and according to the relevant research literature (Arroyo-Toledo et al., 2021; Cerezuela-Espejo et al., 2018; Huerta Ojeda et al., 2018; Pinot & Grappe, 2014).

For swimming, the assessment was based on a 200m time trial (T200m) conducted in a 25-m indoor pool at 26º C. Z3 training was set at speeds above 86% of T200m; Z2 was set at speed between 76 and 85%, and Z1 below 75% of T200m test (Arroyo-Toledo et al., 2021).

For cycling, participants used their own bicycles equipped with an ergometer and pre-calibrated personal power meters. Performance was assessed on the basis of a 4-minute time trial (T4min). It was determined that Z3 training would be performed above 76% of the average power output of T4min; Z2 between 61% and 75%, and Z1 for power outputs below 60% (Pinot & Grappe, 2014). In addition, a 20-minute time trial (T20min) was also included for a more comprehensive assessment of performance, which has shown a strong correlation with direct identification of power at the IAT (Borszcz et al., 2018; Sitko et al., 2022; Valenzuela et al., 2021).

The assessment assigned for running was based on a 6-minute time trial (T6min) performed on a 400-m track. The training programmed proposed for Z3 was designed for speeds above 86% of the average T6min speed, while the Z2 training programme was designed for speeds between 66 and 85%. The Z1 training programme was designed for speeds below 65% of T6-min (Cerezuela-Espejo et al., 2018; Huerta Ojeda et al., 2018).

Prior to each application of the time trial performance tests, all triathletes were required to complete a standardized warm-up routine. The warm-up, comprising 20 minutes of exercise at Z1 intensity, followed by five minutes of specific activation exercises. The athletes were provided with explicit instructions regarding the duration and format of each test.

Additionally, based on the data from the time trial performance tests, their coach (TR) prescribed the training program based on time targets to track each zone and monitor the TRIMPs (Foster et al., 2001). Thus, heart rate (HR) and rate of perceived exertion (RPE) were mainly used for the prescription of long-duration and low-intensity training (i.e., Z1), and the speed-power, and RPE scales were used for the prescription of moderate and high-intensity training (i.e., Z2 and Z3). Athletes recorded all training sessions with their HR monitor (HR; Polar Electro, Kempele, Finland) and then uploaded their data into a specific analysis software (Training Peaks®, USA).

The three-zone model, related to HR and RPE, plays a crucial role in our performance assessment guidelines:

1. Z1: Low Intensity, <82%HRmax, RPE <4 points.
2. Z2: Moderate Intensity, 76-85% T200m; 61-75% T4min; 66-85% T6min; 82-92% HRmax; RPE >4, <7 points.
3. Z3: High Intensity, >86% T200m; >76%T4min; >86%T6min; >92% HRmax, RPE >7 points.

Training intervention

To reduce the effects of previous training, a pre-experimental period consisting of one week of detraining and 3 weeks of controlled training was proposed, with 95% of the prescribed sessions in Z1 and the remaining 5% in Z2.

The training program consisted of a combination of low and high-intensity sessions, Z1 and Z3, respectively. The sessions in Z1 lasted between 60 and 180 minutes, and those in Z3 between 40 and 60 minutes. Three sessions in Z3 were proposed weekly, one for each discipline interspersed with six training sessions in Z1 (Figure 1), assigning 75% of the training volume to Z1, 0% to Z2, and the remaining 25% to Z3. The intensity distribution was set according to the Polarization Index (PI): PI = log10 (Z1/Z2 x Z3*100) proposed by (Treff et al., 2019). If IP >2.00, the methodology can be defined as 'polarized'. Conversely, if IP is ≤ 2.00, the methodology is described as 'non-polarized'. This intervention presented a PI = 3.2, values in line with those proposed in the training of elite cyclists (Schneeweiss et al., 2022) but higher than studies conducted with recreational triathletes and elite runners (Filipas et al., 2022; Röhrken et al., 2020).

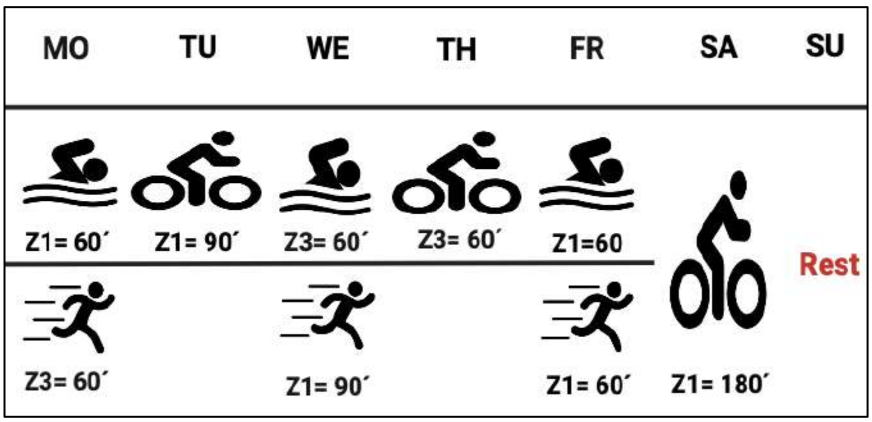

Figure 1. Weekly training programme that was implemented during the 13-week intervention period. The training programme consisted of two distinct intensity levels, designated as Z1 (low intensity) and Z3 (high intensity).

Statical analysis

JAMOVI® version 2.3.21 for Windows (Sydney, Australia) software was used for statistical analysis. Variables and standard deviations by pre- and post-test were presented to describe the study variables. The percentage of changes in the CRF variables (%Δ) was calculated using the following equation: ([post-test - pre-test]/pre-test) × 100%. First, a normality test was performed using the Kolmogorov and Smirnov test. Then an analysis of covariance (ANCOVA) was applied to establish differences between pre- and post-intervention for each test, with Bonferroni's post-hoc to establish the differences obtained by each group. In addition, the effect size was calculated using the partial eta-square test (η^2p), considering the following classification: <0.01 (small), >0.06 (moderate), >0.14 (large) and >2.0 (very large) (Richardson, 2011). In all tests, a value p < .05 was considered significant.

RESULTS

After the medical examination, 23 athletes were included in the study and assigned to an intervention group, POL (n = 23). Due to health complications, 10 athletes could not complete all assessment from the beginning to the end of the study. Finally, 13 data sets were comprehensively analysed.

The results of a 13-week POL intervention program in the swim time on 200m showed a decrease in the duration of the test of 4.48%, throwing non-significant differences between the pre- and post-intervention results (*p* = .59). Power in Bike on 4 and 20 min increased 6.20% and 5.29%, however the difference was not significant (*p* = .50, *p* = .62) respectively. In the 6min run test there was an increase in running speed of 0.94%, but this difference was not significant either (*p* = .58) (Table 2).

Table 2. Performance data from the pre and post-test. Data are means (±SD).

Test and variable	Pre	Post	Dif.	(%∆)	*p*	n2p	Pb
Swim T200m. (min/s)	3.03 ± 0.58	2.90 ± 0.53	0.12	-4.48%	.59	0.01	0.592
Bike T4min. (power, W)	272.09 ± 55.91	290 ±69.33	18.4	+6.20%	.50	0.02	0.502
Bike T4min. (W/kg)	4.04 ± 0.78	4.27 ± 0.83	0.23	+5.38%	.50	0.02	0.502
Bike T20min. (power, W)	204. 91 ± 51.3	216.36 ± 56.6	11.5	+5.29%	.62	0.01	0.624
Bike T20min. (W/kg)	3.04 ± 0.67	3.18 ± 0.70	0.14	+4.40%	.62	0.012	0.627
Run T6min. (Km/h)	15.71 ± 1.69	15.86 ± 1.54	0.15	+0.94%	.82	0.002	0.825
HRmax. (bmp)	184.91 ± 8.0	187.09 ± 10.12	2.18	+1.16%	.58	0.015	0.583

Note: Pre, pre-test; Post, post-test, Dif, ; p, ; %, ; n2p: the partial eta-square test ; Pb: Bonferroni's post-hoc; Swim T200m (min/s), time on 200m test; Bike T4min, power on 4min test; Bike T20min, power on 20 min test; Run T6min (km/h), velocity on 6 min test. HRmax, maximal heart rate.

DISCUSSION

Our results, provide a comprehensive understanding of the effect of the POL model on time trial performance in athletes classified as trained and highly trained (tiers 2 and 3, respectively). We demonstrate that a 13-week training period using a POL TID (Z1 = 75%; Z2 = 0%; Z3 = 25%, IP: 3.2) did not significantly change time trial performance in any of the tests performed.

These findings contradict the results of the meta-analysis developed by (Rosenblat et al., 2019), where POL model demonstrated a positive impact and superiority over the THR training model in improving time trial performance. However, it is important to note that participant classification framework of the athletes included in our study was lower than that reported in the meta-analysis above. Consequently, the efficacy of the POL model has only been demonstrated in elite and world-class endurance athletes (tiers 4 and 5, respectively) (Pla et al., 2019; Yu et al., 2012). They are supported because these athletes, often professionals, tend to have more time to train and recover from training than lower- level endurance athletes, allowing them to complete a greater volume of training usually prescribed in Z1 (i.e., low-intensity zones) (Burnley et al., 2022). In addition, there are notable differences in how elite/ world class endurance athletes and non-elite athletes respond to endurance training programs (Silva Oliveira et al., 2024). Elite athletes can effectively tolerate high training volumes at Z3 due to their high physiological capacity (Magalhães et al., 2024). In contrast, for non-elite athletes with lower physiological capacity, these high training volumes at Z3 may result in inadequate recovery and increase the risk of non-functional overtraining (Meeusen et al., 2013). Therefore, while the POL approach may be optimal for athletes with high physiological capacity, lower-level endurance athletes may have better options.

Previous studies (Rønnestad & Hansen, 2018), suggest that 480-720 min per week of training in Z1 could be optimal for inducing performance improvements in elite cyclists (i.e., level 4). However, this claim does not have sufficient scientific support to be extrapolated to trained and highly trained athletes (i.e., tiers 2 and 3, respectively). In our study, the average weekly training volume allocated in Z1 was ∼540 min. However, we could not observe significant improvements in time trial performance in any of the tests evaluated. For this reason, increasing the training volume in Z2, traditionally associated with THR and PYR models, could effectively promote significant changes in sports performance in trained and highly trained athletes (tiers 2 and 3, respectively) (Festa et al., 2019).

Regarding physiological mechanisms, scientific evidence supports the use of Z2 training as a valid method to promote endurance adaptations and performance improvements in endurance athletes (Tønnessen et al., 2020). The evidence suggests that training volume at this specific intensity range optimizes lactate removal from muscle (Casado et al., 2023) and glucose utilization via the oxidative pathway during exercise (Casado et al., 2023). In addition, as with Z3 training, an increased in mitochondrial proliferation through PGC1α activity, mediated by elevated AMPK activation, has been evidenced (Gibala et al., 2012; Granata et al., 2018). However, it is possible that Z2 training will optimize the number of recruited motor units without the adverse effects associated with elevated catecholamine levels reported with Z3 training (Casado et al., 2022). In this regard, (Magalhães et al., 2024) have demonstrated a positive correlation between Z2 training time and the improvement in power output associated with 4 mmol lactate (P4) in a group of recreational cyclists after 16 weeks of training. Similar results were observed in trained triathletes after 13-weeks of training (Selles-Perez et al., 2019), in which time spent training in Z2 was associated with superior performance in a Half-Ironman race. Both programmed were designed using a PYR model (i.e., Z1>Z2>Z3) (Treff et al., 2019).

On the other hand, the analysis of the studies (Magalhães et al., 2024; Selles-Perez et al., 2019) indicates that the intervention period could also influence changes in performance capacity. In comparison to other TID models, longer training periods with a longer POL training report smaller improvements in endurance performance. In this sense, research development by (Silva Oliveira et al., 2024) has shown that the effectiveness of POL training in improving physiological capacity and endurance performance is greater when the intervention is shorter, at 12 weeks. Our results are in agreement with those obtained by these authors (Silva Oliveira et al., 2024), since we did not observe any significant changes in any of the variables studied during the 13 weeks of intervention. Similar results were observed by (Filipas et al., 2022), who compared the effects of 16 weeks of two different training intensity distribution models (POL and PYR) and two sequences of these modalities (POL+PYR and PYR+POL) on time trial performance in a 5 km race in highly trained runners (i.e., tier 3). All models improved performance in the 5 km test. However, only the POL group showed significant improvements in the first 8 weeks, which levelled off over time and were similar to the other models by the end of the study. These results suggest that when training interventions last 12 weeks or more, the effects of the POL training method on performance may be reduced.

In light of the existing literature, (Burnley et al., 2022; Foster et al., 2022; Silva Oliveira et al., 2024), coaches should exercise caution when employing the POL model to enhance time trial performance in trained and highly trained-level athletes (i.e.., tier 2 and 3, respectively). It has been observed that this methodology may not be effective, particularly in training programs that exceed 12 weeks in duration. Given the above, it is essential to consider that the methods that prove effective for world-class athletes may need to be more effective for trained and highly trained athletes.

Our study has some limitations that may affect the quality of this research:

1. We used short-duration tests (200-m in swimming, 4 and 20-min in cycling, and 6-min in running) before and after the training intervention. These protocols may not directly represent performance in longer distance events (e.g., Half Ironman Triathlon). However, they represent a practical, effective, and time-efficient form to quantify the effect of the training program.

2. Throughout the intervention, we experienced a high drop-out rate of athletes (n = 10). This situation considerably reduced the sample size (n = 13) and weakened the study's statistical power.

3. We allocated a high percentage of the training volume to Z3 (25% of the total training time). These values are high when compared to other recent studies (Festa et al., 2019; Filipas et al., 2022; Röhrken et al., 2020).

4. No indirect calorimetry or blood lactate measurement assessments were carried out. Therefore, it was not possible to investigate the energy cost of sport-specific movement patterns (economy of movement in ml O2/kg/km), VO2max or the velocities and powers associated with the two physiological thresholds, which are considered to be the determining variables of endurance performance (Joyner et al., 2020; Midgley et al., 2007; Pate & Branch, 1992).

These limitations should be considered when interpreting the study's results and designing future research in this field.

CONCLUSSION

In the present study of trained and highly trained triathletes, a TID with a POL approach did not significantly improve any of the time trial performance tests studied after a 13-week training programme. Despite the importance of training time allocated to Z1 and Z3, our results suggest that optimal training programmes for this performance classification framework should not preclude the prescription of training in Z2. In this sense, to maximize the adaptations that POL training can produce, coaches should consider the athlete's initial level of performance as well as the intervention time of the POL model.

Future studies are needed to investigate the effect of different training intensity distributions models in groups with different performance levels and its impact on time trial and competition performance.

AUTHOR CONTRIBUTIONS

Study concept and design, article writing: Tomás Rivera-Kofler. Critical review: Guillermo Cortés-Roco, Tomás Rivera-Kofler, and Rodrigo Yañez-Sepulveda. Data collection: Tomás Rivera-Kofler, Rodrigo Yañez-Sepúlveda, and Guillermo Cortés-Roco. Analysis: Guillermo Cortés-Roco and Tomás Rivera-Kofler. Final approval of the version to be published: Tomás Rivera-Kofler, Rodrigo Yañez-Sepúlveda, Guillermo Cortés-Roco, Exal García-Carrillo, and Jorge Olivares-Arancibia.

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Brain activity and motor performance under different focus of attention in shooting of elite archer: An fNIRS study

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ABSTRACT

The correlation between different focuses of attention (FOAs) and performance in archery had been insufficiently explored. This study aimed to investigate brain activity under different FOAs, quantify the relationship between FOA and arrow scores in shooting. Sixteen elite archers were recruited to participate in this study. A 48-channel portable fNIRS device was used to collect hemodynamic signals in an outdoor environment. Each archer shot five arrows at a target placed 70 meters away. The results showed that motor performance at external and internal focus are not reach the statistical difference ($t = 0.527$, $p = .606$, Cohen's $d = 0.117$). compared to IF, EF have lesser ΔHbO in channel 14 ($t = -2.218$, $p = .044$, Cohen's $d = 0.640$), channel 30 ($t = -2.306$, $p = .042$, Cohen's $d = 0.598$) and channel 42 ($t = -3.506$, $p = .005$, Cohen's $d = 1.012$), but have greater ΔHbO in channel 37 ($t = 2.638$, $p = .023$, Cohen's $d = 0.762$), channel 38 ($t = 2.631$, $p = .023$, Cohen's $d = 0.759$). Additionally, compared to IF, EF have greater neural efficiency in channel 28 ($p = .026$). Compared to IF, EF enhanced activity in the visual cortex, particularly in V2 and V3, while decreasing activity in M1, S1, PMC, and SMA. Additionally, EF demonstrated greater neural efficiency in PMC and SMA. However, under IF, archers allocated additional resources to PMC and SMA to maintain performance levels comparable to those under EF.

Keywords: Performance analysis, Archery, fNIRS, External focus.

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INTRODUCTION

Archery is a sport that emphasizes accuracy (Ahmad et al., 2014). Archers need to shoot the arrow at the small bullseye from a distance of 70 meters. They must carefully control their movements and use muscle memory to control the bow (Yapıcı et al., 2018). In this situation, archers must not only complete their movements precisely, but also face many challenges from the environment, such as wind, noise, and other factors. These factors impact athletes and shift their attention away from the task of shooting. A classic example is Matthew Emmons, who missed his target in the final of the 50-meter rifle three positions event at the 2004 Athens Olympics. He may have failed to inhibit distractions from another shooter's target (Lu et al., 2021). Therefore, allocating attention resources is important for athletes who shoot.

When discussing the focus of attention (FOA), the well-known theory of external focus (EF) and internal focus (IF) highlights their differing impacts on motor performance. Wulf and colleagues have conducted extensive research in this area, they suggest that IF is harmful to performance, while EF is beneficial (Nicklas et al., 2024). The definitions of EF and IF have been described in previous studies. Briefly, EF refers to focusing on external objects, while IF refers to focusing on internal sensations. For example, when hitting a volleyball toward a mark on the wall, focusing on the mark indicates EF, while focusing on the sensation of the ball contacting your wrist indicates IF (Teasdale & Simoneau, 2001). Many studies have demonstrated that EF enhances performance in various tasks, such as dart throwing (Hitchcock et al., 2018), balance control (Sherman et al., 2021), and golf swings (Bell & Hardy, 2009). Regarding the mechanism, Wulf claims that IF shifts attention away from external tasks, increases anxiety, and heightens self-consciousness, which disrupts the automatic processes of motor control. In contrast, EF focuses attention away from the body's movements, facilitating the central nervous system's use of pre-planned motor programs to control movements (Wulf & Lewthwaite, 2019).

However, in archery, there is a lack of high-quality research comparing the effects of EF and IF on performance. Some studies suggest that archers should use EF to achieve better performance (Vrbik et al., 2021; Wang et al., 2022). Haywood claims that elite archers shift their focus to external targets before shooting (Haywood, 2006). However, these studies have limitations. They did not analyse the relationship between focus and performance or use neuroimaging to examine the brain activity of archers during different focus tasks. Archery may differ from other sports in terms of attention focus. According to the quiet eye theory, the duration of the quiet eye plays an important role in shooting performance (Behan & Wilson, 2008; Kim et al., 2019). However, if athletes focus externally, such as on the relative position between the sight and target, they may be distracted by sight motion and moment-to-moment adjustments (online error corrections), resulting in shorter QEDs and larger errors (Gonzalez et al., 2017). Meanwhile, this type of distraction is difficult to avoid because, in archery, athletes must shoot at a target 70 meters away. The target is so small that even tiny movements can cause significant shifts in their vision. To explore whether archers benefit from external focus, the best approach is to use neuroimaging tools and analyse the relationship between brain activity and performance. Although some researchers have used fMRI and EEG in this field, they typically focus on differences in brain activity between elite and amateur archers (Gu et al., 2022; Kim et al., 2008; Kim et al., 2014) or the effects of different training methods on archers (Chuang et al., 2015; Gao & Zhang, 2023). There is still a lack of understanding regarding the relationship between different attention focuses and shooting performance.

In summary, we use fNIRS to study archers' shooting performance under EF and IF in outdoor settings. By analysing motor performance and neural brain activity, we aim to assess the impact of different attention focus tasks. We believe this approach enhances the ecological validity of research in real training environments. We hypothesize that: 1) EF leads to better performance compared to IF; 2) EF results in higher activity in brain areas associated with movement and vision compared to IF; 3) EF promotes the automatic of brain areas related to motor control. We believe that exploring the relationship between attention focus and performance will deepen our understanding of archery and human attention control.

METHODS

Participants

We recruited 16 professional archers (age: 16.4 ± 1.2 years; height: 172.3 ± 3.5cm; weight: 72.2 ± 5.6 kg;) for this study. These participants were selected from the National Outdoor Archery Championship held in Lai Xi City from June 16 to June 20, 2024. These athletes are the top 16 in the elimination phase in this competition, so they represent the elite level of adolescent archers in China. The inclusion criteria were: 1) at least four years of training experience; 2) regular training maintained over the past six months; 3) male; and 4) right-handed, defined as using the left arm to hold the bow and the right hand to pull the string. The exclusion criteria were: 1) shoulder injuries, lower back pain, or other injuries within the past three months; and 2) consumption of caffeine or alcohol within 24 hours prior to testing. All participants and their coaches were informed of the risks involved in this study, and all participants volunteered to take part. They provided written informed consent after receiving a detailed explanation of the study, This study was approved by the Ethics Committee of Qufu Normal University (grant number: LL-20240005). All procedures were conducted in accordance with the latest guidelines and regulations of the Declaration of Helsinki.

Experimental procedure

The study was conducted in an outdoor field, with a target set 70 meters away from the participants. This distance was consistent with Olympic archery standards. A standard 120 cm target paper was fixed to the target. Specifically, according to the World Archery Federation standards, the target paper had five different colours, each representing a specific score range. The bullseye was yellow and scored 10 or 9 points; the red area scored 8 or 7 points; the blue area scored 6 or 5 points; the black area scored 4 or 3 points; and the white area scored 2 or 1 point.

All participants used their own bows and equipment and were allowed to shoot three or four arrows to adjust their sights before the formal tests. Then, participants wore portable fNIRS devices during the formal tests. This study used a block design. Participants rested for 30 seconds, then had 30 seconds to prepare to shoot, followed by another 30 seconds of rest, and so on. Participants shot 6 arrows in each task (see Figure 1). Participants completed tests under two different tasks, namely EF and IF. The sequence of these tasks was randomized. During EF and IF tasks, the author of this paper gave verbal instructions to the participants (Vrbik et al., 2021):

1) EF instruction: Please focus on sight's pin stable within the bullseye, try to fix it in a way to concentrate on your sight's pin and letting it melt with the centre and on the follow-through and arrow flight.
2) IF instruction: Please focus on the sensations in your bow arm and string arm and other body parts, try to use the muscle memory in the training, to locate the bow position and complete the stable shot.

To ensure that athletes understand the concept of different focuses of attention, they were asked to repeat the instructions for each task. If their repetition was correct, it was considered that they had understood the instructions. Additionally, to minimize potential confounding effects, participants were instructed to avoid unnecessary movements, such as clenching their teeth or making facial expressions, during the testing process.

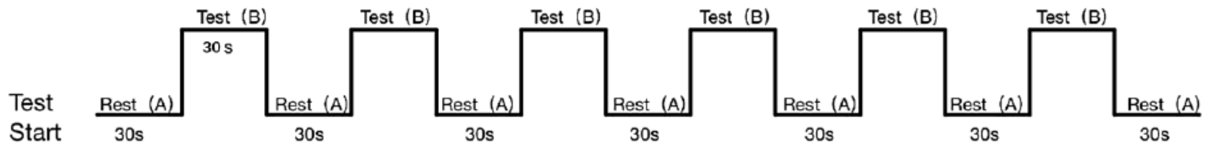

Figure 1 The block design of this study.

Data collection

Hemodynamics

The portable fNIRS devices (Model: NirSmart-3000A, Danyang Hui Chuang Inc., China) were used to collect hemodynamic signals. These devices had 24 emitters, 16 detectors, and 48 channels. The distance between emitters and detectors was 3 cm, the sampling rate was 11 Hz, and the wavelengths were 730 nm and 850 nm. The locations of the probes were localized using a 3D digitizer. The spatial arrangement of the 48 channels on standard brain templates from the Montreal Neurological Institute (MNI) was imported into the NIRS-SPM toolbox (Ye et al., 2009) to obtain spatial distributions and probabilities for each channel. The region of interest in this study includes frontopolar cortex, orbitofrontal cortex, primary motor cortex, pre-motor cortex, supplementary motor cortex, primary somatosensory cortex and visual cortex. When placing the devices on the participant's head, the hair was carefully adjusted to ensure the detectors and emitters were as close to the scalp as possible. During the formal tests, a black blanket was used to cover the head to minimize the impact of sunlight on the signals.

Motor performance

After each shot, an expert observer used a telescope (Model: Ultima-80, Celestron Inc., USA) to observe the arrow's location on the target paper and record the corresponding ring. If the arrow was a line cutter, it was awarded the higher score. For example, if the arrow touched the 9-ring line, the score was recorded as 9.

Data analysis

Raw data were exported from the fNIRS devices and converted from NIRS format to SNIRF format using Homer3 (Version: 1.87, Boston University, USA). The raw data were visually inspected, and poor-quality channels were marked and excluded during data processing. The data processing pipeline included several steps. First, the light intensity was converted to optical density. Next, motion artifacts were corrected channel-by-channel to address spikes in the data. Wavelet functions were applied to correct noise caused by head movements. A 0.01-0.1 Hz bandpass filter was used to remove device and physiological noise, including Mayer waves (≈0.01 Hz), breathing (0.2-0.3 Hz), and heart rate (1.6-1.8 Hz). The modified Beer–Lambert Law was applied to convert optical density data into concentrations of oxyhaemoglobin (HbO). The mean value of HbO within the last 5 s of each rest period was selected as a baseline for correction, The mean values represented the change in HbO and HbR concentrations from 0 seconds before the task to 30 seconds after the task began.

The scores were organized and saved in Excel. Meanwhile, methods from previous studies were used to quantify neural efficiency between different FOAs (Curtin & Ayaz, 2019; Curtin et al., 2019). Specifically, neural efficiency was defined as the relationship between outcomes (scores) and effort (hemodynamics). The scores and ΔHbO concentrations were normalized using the Z-Score method and then projected into a two-dimensional coordinate system. The "*zero-efficiency*" line, representing outcome = effort, was calculated.

The distance between this line and each data point (score) was then determined. According to previous studies, neural efficiency can serve as an indicator of automaticity of brain areas (Callan & Naito, 2014).

Statistical analysis

SPSS (Version 26.0, IBM Inc., USA) was used for statistical analysis. First, the normality of the data (hemodynamics and scores) was checked for the two different tasks. If the data were normally distributed, a paired-samples t-test was used to assess differences between EF and IF tasks. If the data did not conform to normality, the Wilcoxon signed-rank test was applied. To avoid the problem associated with multiple comparisons, a false discovery rate (FDR)-corrected was considered. Cohen's *d* was reported as the effect size, with the following interpretation standards: 0.8 (large), 0.5 (medium), and 0.2 (small) (Sawilowsky, 2009). Pearson correlation analysis (for normally distributed data) or Spearman correlation analysis (for non-normally distributed data) was conducted to examine the relationship between hemodynamics and scores. Data in the results were expressed as means and standard errors.

To ensure the statistical power was valid, the post hoc power estimation function in G*Power (Version 3.1.9, Heinrich Heine University Düsseldorf, Germany) was used to calculate the actual power. The effect size of ΔHbO from channel 37, 0.762 (see the "*Hemodynamics Data*" section), was used. The number of groups was set to 2, the sample size to 16, and the α error probability to .05. The resulting actual power was 0.896.

RESULTS

Hemodynamics data

Five channels showed the statistical significance between EF and IF tasks, specifically, compared to IF, EF have lesser ΔHbO in channel 14 (t = -2.218, *p* = .044, Cohen's *d* = 0.640), channel 30 (t = -2.306, *p* = .042, Cohen's *d* = 0.598) and channel 42 (t = -3.506, *p* = .005, Cohen's *d* = 1.012), but have greater ΔHbO in channel 37 (t = 2.638, *p* = .023, Cohen's *d* = 0.762), channel 38 (t = 2.631, *p* = .023, Cohen's *d* = 0.759), as shown in Table 1. Please see appendix to check the results of other channels.

Table 1. The ΔHbO (× 10−5 mmol/L) channels with statistical significance in EF and IF tasks.

Brain area	Channel	EF	IF	t	*p*
Left hemisphere PMC and SMA	14	3.05 ± 0.81	4.66 ± 1.25	-2.218	.044
Left hemisphere S1	30	2.01 ± 0.81	3.32 ± 1.06	-2.306	.042
Right hemisphere M1	42	1.43 ± 0.59	3.18 ± 1.09	-3.506	.005
V2	37	4.36 ± 1.36	1.28 ± 1.11	2.638	.023
V3	38	4.81 ± 0.66	2.32 ± 0.73	2.631	.023

Note. SMA: Supplementary Motor cortex. PMC: Pre-Motor cortex. S1: Primary Somatosensory cortex. M1: Primary Motor cortex. IF: internal focus. EF: external focus.

Motor performance

The scores between EF and IF tasks did not reach the statistical significance (t = 0.527, *p* = .606, Cohen's *d* = 0.117), as shown Figure 2.

Correlation between hemodynamics and motor performance

Correlation analysis was conducted to examine the relationship between hemodynamic features and scores. The results showed that there was a negative correlation between channel 28 (r = -0.769, *p* = .003) hemodynamic and performance in the EF task, positive correlation between channel 14 (r = 0.626, *p* = .029) in the IF task, as shown in Table 2.

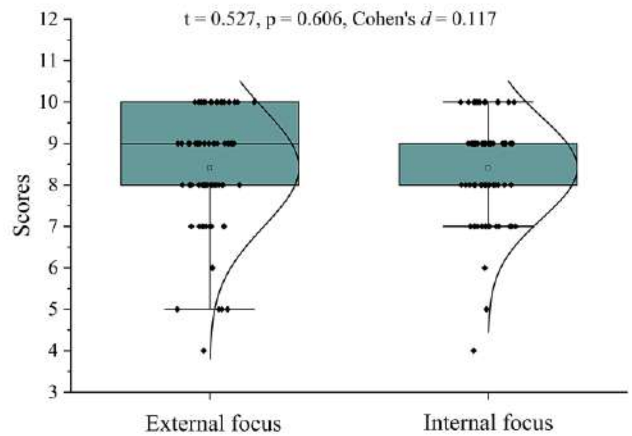

Figure 2 Motor performance in EF and IF tasks with statistical results. Each scatter point represents an individual shot.

Table 2 The correlation between ΔHbO of channels and motor performance with statistical significance in EF and IF tasks.

Brain area	Channel	Task	r	*p*
Left hemisphere PMC and SMA	14	IF	0.626	.029
Left hemisphere PMC and SMA	28	EF	-0.769	.003

Note. SMA: Supplementary Motor cortex. PMC: Pre-Motor cortex. IF: internal focus. EF: external focus.

Neural efficiency difference between two tasks

One channel showed the statistical significance between EF and IF tasks, specifically, compared to IF, EF have greater neural efficiency in channel 28 (*p* = .026), as shown in Figure 3.

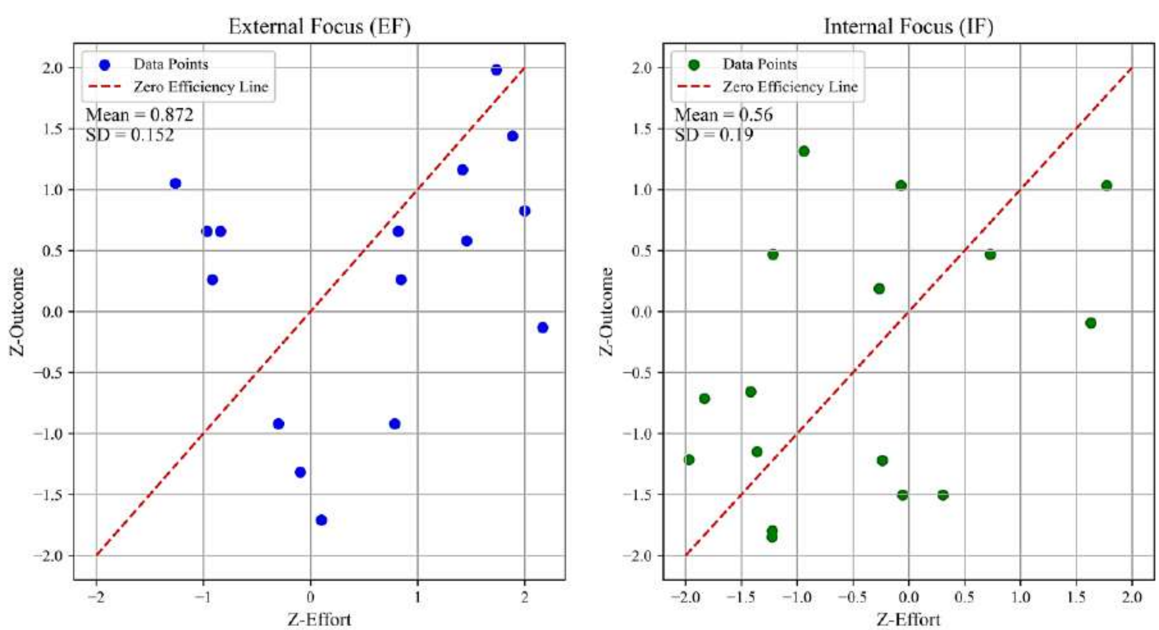

Figure 3 Neural efficiency with channel 28 in EF and IF tasks. Each dot represents the z-score of an individual shot. Higher efficiency is indicated by data points closer to the upper-right corner.

DISCUSSION

The relationship between focus of attention and performance in archery has not been thoroughly explored. In this study, we used portable fNIRS devices to investigate this relationship. The results showed that compared to IF, EF elicited greater brain activity in the V2 and V3 cortex, but has less activity in the left hemisphere PMC, SMA, S1 and right hemisphere M1. This finding is consistent with our first hypothesis. Meantime, we did not find a difference between EF and IF at shooting performance, but hemodynamic features have negative and positive correlation with scores in the EF and IF respectively, which is inconsistent with our second hypothesis. Additionally, the neural efficiency in PMC and SMA is greater in EF, which is consistent with our third hypothesis. These results are discussed in the following sections.

Results showed that EF elicited significantly higher activation in certain areas compared to IF. These results are consistent with our task design. Specifically, EF showed greater activation in V2 and V3. From V2 to V3, the numbers of direction-sensitive neurons in V2 and V3 continue to growth (Foster et al., 1985; Gegenfurtner et al., 1997). These neurons are highly sensitive to object movement (Essen & Zeki, 1978) (Furlan & Smith, 2016). So when athletes focused on the relative positions between sight and target, V2 and V3 will activate greater to processing the visual information. These can be explained that why EF have higher activation in these two areas, previous studies has been confirmed that in rifle shooting, athletes will activate these areas to finish aiming process. They also claimed that visual cortex greater activation may have harmful to shooting performance (Loze et al., 2001), because more resources input will decrease the resources input at M1, PMC and SMA areas which helpful for precisely motor control. Elite shooters usually activate their visual cortex only extremely short duration before pulled the trigger (Doppelmayr et al., 2008).

IF has greater activity in S1, M1, PMC, and SMA is interesting results. Greater activity in these areas means highly resources input. For prospective of archery skills, continues, smoothly sequencing to execute the technique movement is crucial for success. PMC and SMA has been shown in previous studies to play an important role in the sequential control of motor actions (Chang et al., 2011; Cona & Semenza, 2017), according to the neural efficiency hypothesis, if the neural efficiency increase, the PMC should exhibit lesser activity, automation level of locomotion increases (Callan & Naito, 2014). So, based on the results of EF have greater neural efficiency in PMC and SMA compared to IF, which means EF have greater automatic of motor control, consistent with constrain hypothesis (McNevin et al., 2003). However, our correlation analysis also supports that PMC and SMA activity increase have positive impact for performance in IF, which means greater activity in PMC and SMA may be associated with athletes are tried to conquer the automatic performance decrease in IF. Previous studies claim that brain will recruit additional areas to compensation and maintain the performance in balance or obstacles negotiation task when challenging increase (Chen et al., 2017; Kan et al., 2025). Meantime PMC and S1, M1 usually simultaneously activate (Urquhart et al., 2019), previous studies claim that the functional connectivity between PMC and M1 enhanced in motor executed and motor imagination (Kim et al., 2018), we believed that greater activity in S1 and M1 at IF have two reasons, one of them from our verbal instruction in IF, namely imagination of inner feeling of body or muscle memory of technique movements, one of them are caused by additional activity of PMC and SMA. We are already know that S1 are mainly responsible to processing the sensory information, such as touching feelings and inner feelings, Previous studies have found that S1 enlargement emerges in tactile-sensitive sports, such as handball (Meier et al., 2016). Greater S1 activity allows athletes to process tactile information from the bow and string more precisely (Davis et al., 2022). Meanwhile, the direct neuronal mapping from S1 to M1 is patterned (Ghosh et al., 1987; Pons & Kaas, 1986), specifically following somatotopic maps. Studies have found that finger sensory information can elicit motor support for the same finger from M1 (Shelchkova et al., 2023). Thus, greater activity of M1 can better utilizes sensory information from S1 to adjust bow stability and anchor positions, achieving consistent and stable shots. Based on the above, we believed that athletes may be through increased activity in PMC, SMA, S1 and M1 to maintain a similar performance of EF.

In summary, we believed that the training and competitive experiences of high-level athletes may help them better adapt to various conditions in training or competition (Song et al., 2024). More specifically, considerate the S1 M1 did not have correlation with performance in IF, athletes through increased additional activity PMC and SMA may is a key factor for maintaining stability of performance. This is a reason of why arrows scores didn't statistical difference between different FOAs. Meidenbauer and colleagues has been prove that there have positive correlation between brain activity and task requirements (Meidenbauer et al., 2021), this kind of requirements are not only task difficulty, but including all features with relation with finish task, even they are focus on the frontal lobe, but also should applicable for others areas. This kind of mechanism may be crucial for humans, as various adaptive motor solutions, supported by the inherent degeneracy of neurobiological systems, can be utilized to allow different system components to achieve the same performance outcomes (Chow et al., 2009; Davids & Glazier, 2010).

The findings of this study could provide valuable insights for coaches and elite archers. In competitive sports, an athlete's ability to quickly and flexibly adapt their strategies to changing environments is crucial for success (Doron & Martinent, 2021; Gaudreau & Blondin, 2004). Archers may struggle to use EF in adverse conditions, such as darkness or rain, as these factors can obscure the target. In such cases, they may have difficulty concentrating on the relative position between the sight pin and the target, making IF a better alternative. However, if the environment permits the use of EF, archers should consider it, as EF enhances neural efficiency and promotes the automation of motor control.

Limitations

We did not collect data from lower-skilled athletes, so we were unable to compare brain activity and performance across different skill levels. This limitation arose because we aimed to collect data in a real-world environment while ensuring that every athlete maintained their optimal condition. To achieve this, we conducted data collection during competition periods. However, due to scheduling constraints, we could not collect data from all athletes. Despite this limitation, we believe that this study remains valuable, as it is the first fNIRS investigation of the shooting process in archery and conducted in a testing environment designed to closely resemble an Olympic field.

CONCLUSION

This study was conducted in a standard Olympic field to quantify the impact of EF and IF on elite archers' performance, hemodynamics, and neural efficiency. The findings revealed that, compared to IF, EF enhanced activity in the visual cortex, particularly in V2 and V3, while decreasing activity in M1, S1, PMC, and SMA. Additionally, EF demonstrated greater neural efficiency in PMC and SMA. However, under IF, archers allocated additional resources to PMC and SMA to maintain performance levels comparable to those under EF.

AUTHOR CONTRIBUTIONS

Kun Qin, Juan Wu, and Shikun Wang made substantial contributions to the conception, design, and execution of this study. Kun Qin: conceptualization, methodology, investigation, writing—original draft preparation, and visualization. Juan Wu: validation, resources, writing—review and editing, supervision, project administration,

and funding acquisition. Shikun Wang: data curation, statistical analysis. All authors have read, revised, and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Analysis of professional basketball team training: Comparing drill types on different playing positions

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ABSTRACT

This study investigates the external load experienced during various game-based drills (GBD) in professional basketball, focusing on the most commonly used formats during the competitive season. External load metrics such as total distance (TD), player load (PL), high-speed running (HSR), accelerations (HI ACC), decelerations (HI DEC), jumps (HI JUMP), and landings (HI LAND) were assessed across different GBD types, including 5vs5, 5vs0, and variations in court size. A total of 12 male professional basketball players participated in the study, with data collected over 46 sessions. Results indicated that 5vs5 and 5vs0 formats were most prevalent, with significant differences in external load depending on court size, opposition presence, and player position. Larger court sizes and drills involving opposition resulted in higher physical demands, particularly in PL, and high-intensity actions, where drills without opposition showed high demands in HSR and HI LAND. Positional differences were observed, with guards and forwards exhibiting greater HSR and higher acceleration/deceleration values compared to centers. These findings provide insights into the external demands of GBD, highlighting the importance of customizing training load based on positional roles and the nature of the drills. The study underscores the need for further research to incorporate both external and internal load measures, including data from official games, to enhance understanding of how GBD formats influence player performance and adaptation.

Keywords: Performance analysis, External load, Physical demands, Training drills, Game-based drills.

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INTRODUCTION

Basketball is an intermittent game, requiring players to perform high-intensity actions such as sprinting, jumping, and rapid changes of direction (Schelling & Torres-Ronda, 2013), followed by low-intensity activities like walking and jogging (Ben Abdelkrim et al., 2010). The high frequency of games played by professional teams and the limited number of weekly training sessions present challenges for coaching staff in preparing players for matches, therefore, it is essential to involve all staff members in planning the training load (Svilar et al., 2018; Svilar & Jukić, 2018).

Games-based drills (GBD) involve one or more players engaging in competitive games against others (O'Grady et al., 2020). These drills are widely used in training due to their ability to mimic competitive scenarios, which enhances players' perception of technical and tactical elements while introducing variations in physiological and physical stimuli (Aguiar et al., 2012; Clemente, 2016). In basketball, there is a growing body of research on GBD, with studies examining physical and physiological responses to different GBD formats (Klusemann et al., 2012; Sampaio, 2009; Schelling & Torres, 2016). Coaches often manipulate game formats by altering conditions such as court size, number of players, and rule modifications (Clemente, 2016). For instance, reducing the number of players in GBD can significantly alter the physical demands of a training session. Evidence suggests that GBD with fewer players elicits greater physical and physiological demands compared to formats with more players (Conte et al., 2015; Klusemann et al., 2012; O'Grady et al., 2020). For example, Schelling & Torres (2016) demonstrated through accelerometry that 3vs3 and 5vs5 full-court GBD resulted in higher external loads compared to full-court 2vs2 and 4vs4. Similarly, Sampaio et al. (Sampaio, 2009) reported that 3vs3 had higher physiological demands than 4vs4, with their study also showing increased post-counter movement jump (CMJ) performance after 4vs4, indicating lower intensity in this game format.

In terms of court dimensions, larger court sizes contribute to higher external and internal loads (O'Grady et al., 2020), while smaller court sizes are associated with increased directional changes and a higher frequency of technical actions (Klusemann et al., 2012; Schelling & Torres, 2016). Additionally, factors like defence type, shot clock restrictions, and non-stoppage drills can further impact external and internal loads (Ballesta, 2019; Ben Abdelkrim et al., 2010; Bredt et al., 2020; Clemente et al., 2014; Conte et al., 2015; O'Grady et al., 2020; Svilar et al., 2019).

Schelling & Torres-Ronda (2016) classified GBD based on the number of players involved, categorizing drills as directed-oriented, special-oriented, and competitive-oriented. Competitive-oriented GBD should be prioritized in-season due to its greater similarity to actual gameplay (Schelling & Torres-Ronda, 2016). When examining positional variations in external load during GBD, centers exhibit higher counts of total and high-intensity accelerations compared to forwards and guards (Svilar et al., 2018). Forwards, on the other hand, show higher numbers of total and high-intensity decelerations. This positional data is valuable for coaches, providing insights into the unique demands of different basketball roles and aiding in accurate quantification of training loads (Svilar et al., 2018). Although research on GBD is growing, further studies are required to explore the external load in most used GBD formats in professional basketball during the competitive season.

Therefore, this study aims to identify the most frequently used GBD formats in professional basketball during the season, analyse the external load of these drills, and compare external load demands according to player position.

METHODS

Participants

Fourteen male professional players who competed in the Spanish second league participated in this observational research (age: 26.3 ± 3.8 years, height: 196.7 cm ± 8.8 cm, body mass: 91.5 kg ± 10.1 kg) (McKay et al., 2022) . One player was excluded due to injury, and another was not part of the team during the whole measurement period. Therefore, a total of 12 players completed the study and they were grouped as follows: guards n = 6 (point guard, shooting guard), forwards = 3 (small forwards and power forwards) and centers n = 3 (Salazar et al., 2020). All players were informed of the aim, risks, and benefits of the study before signing written consent to allow the collection of data for scientific purposes. This study was approved by the Research Ethics Commission of the University (CIPI/18/195), with all procedures conducted following the Declaration of Helsinki.

Design and procedures

Measurements were conducted during the second half of the 2022-2023 regular season, spanning from February to June. In total, 46 basketball sessions were recorded over 13 weeks. Furthermore, only training sessions that involved contact were analysed. All training sessions were planned and organized by the coaching staff. Data collected during warm-ups and breaks were excluded from the analysis to ensure that the results reflected only the external demands of GBD. During the week, the team typically had five basketball sessions (~5·wk^{-1}), three strength training sessions (~3·wk^{-1}), and usually one game. Before each training session, players wore a vest with a GPS device placed on their upper back. GBD was organized based on the number of players, opposition, and court size (O'Grady et al., 2020). We analysed various versions of competitive 5vs5 drills, including drills with 5 players from one team without opposition (5vs0). Half-court GBD was played on only one half of the court, and full court GBD involved a single transition from both teams (Schelling & Torres, 2016). GBD with 1.5 courts started by playing on one half of the court and then involved 2 transitions (Vazquez-Guerrero et al., 2020), where GBD 2+ courts involved more than 2 transitions. 5vs5 live games were GBD where both teams played continuously without stopping the clock and without breaks.

External demands were classified as: total distance (TD) in meters (m), player load (PL), high-speed running distance (HSR) above 18 km·h^{-1} (García et al., 2020, 2022), number of high-intensity accelerations (HI ACC), number of high-intensity decelerations (HI DEC) surpassing 3.5 m·s^{-1} (Svilar et al., 2019), number of high-intensity jumps (HI JUMP), and number of high-intensity landings (HI LAND), representing impacts above 5G-force (Vázquez-Guerrero et al., 2018; Vazquez-Guerrero et al., 2020; Vázquez-Guerrero et al., 2020). PL is a variable used to measure the total body load of athletes across three axes: vertical, anterior-posterior, and medial-lateral. It is commonly utilized to evaluate neuromuscular load among various types of players (Gómez-Carmona et al., 2020). The external load was measured using the WIMU PRO™ system (Realtrack Systems S.L., Almería, Spain), which has been tested for test–retest reliability (%TEM: 1.19), inter-unit reliability (bias: 0.18), and ICC values of 0.65 and 0.88 for x and y coordinates, respectively (Bastida Castillo et al., 2018). The system, consisting of four 3-axis accelerometers, a gyroscope, a 3D magnetometer, a barometer (sampled at 100 Hz), and an ultra-wideband positioning system (sampled at 18 Hz), was used during training sessions where antennas were consistently positioned in the same location and activated sequentially, with the master antenna always activated last (Serrano et al., 2021). The SPRO™ (version 950, RealTrack Systems, Almería, Spain) software was used for the analysis of the GPS data, and all data was exported to Microsoft Excel, where further analysis was conducted.

Statistical analysis

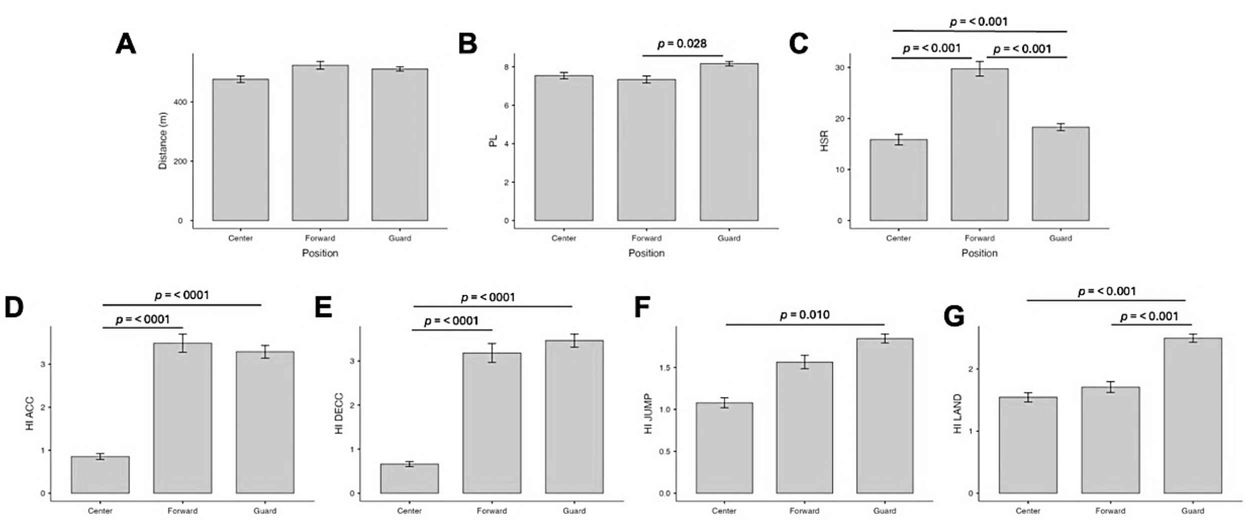
Data normality (Kolmogorov–Smirnov test) and homoscedasticity (Levene's test) were assessed prior to statistical analysis. Normal distribution was confirmed using the Shapiro–Wilk test, and homogeneity of variances was validated by Levene’s test (p > .05). A two-way analysis of variance (ANOVA) was applied to each dependent variable, with exercise type and position as factors. When significant differences were detected, a Bonferroni post hoc comparison was performed. Data are presented as mean ± standard deviation (SD). Statistical analyses were conducted using SPSS software (version 26.0, SPSS Inc., Chicago, IL), with the significance level set at α = .05.

RESULTS

A total of 55 distinct GBD were recorded during practices, with 5vs0 and 5vs5 variations accounting for 58% of the sessions, where GBD with and without opposition were 79.8% vs 20.2% respectively. The absolute mean ± SD values of external load for various GBD are presented in Table 1.

The half-court GBD showed the lowest values for TD, PL, HSR, and HI ACC. The highest PL and TD values were observed in the 5vs5 1.5 court GBD, while the highest HSR was recorded in the 5vs0 2+ court, with no significant difference when compared to the 5vs5 1.5 court GBD. In half-court GBD, TD, PL, and HI JUMP were lower in drills without opposition. In Full court GBD, significant differences were observed for TD, HSR, and HI LAND, with these values being higher in drills without opposition.

Figure 1 illustrates the absolute differences in external load variables across positions. No positional differences were observed for TD.



Note: GBD- game-based drill; A) TD- Total distance; B) PL-Player load; C) HSR- High-Speed Running; m, meters D) HI ACC-High intensity acceleration; E) HI DEC- High intensity deceleration; F) HI JUMP- High intensity jumps; G) HI LAND- High intensity landings.

Figure 1. Comparison of total external load based on players positions.

For PL, significant differences were found between forwards-guards (FG) (7.3 ± 3.7 vs. 8.2 ± 3.9, respectively). For HSR, differences were observed between all positions: center-guards (CG), center-forwards (CF), and FG (15.9 ± 23.1 vs. 18.3 ± 21.8; 29.7 ± 29.5 vs. 18.3 ± 21.8, respectively).

Table 1. Differences in training load indicators according to the basketball exercises.

Drill	Distance (m)	PL	HSR	HI ACC	HI DECC	HI JUMP	HI LAND
5:0 1.5 courts (1)	$466.0 \pm 166.4^{3.4.5.7}$	$6.9 \pm 2.3^{3.4.5.7}$	$27.2 \pm 26.7^{2.4.8}$	2.6 ± 3.4	2.9 ± 4.1	1.3 ± 1.1^{5}	2.3 ± 2.0
5:0 2+ courts (2)	$324.7 \pm 79.4^{3.5.7}$	$4.4 \pm 1.1^{3.5.6.7}$	$70.1 \pm 52.9^{3.4.6.7.8.9}$	5.4 ± 3.0^{4}	$5.5 \pm 3.7^{4.8}$	$1.5 \pm 1.2^{4.5}$	1.5 ± 1.1
5:0 Full court (3)	$697.2 \pm 225.5^{4.6.7.8.9}$	$9.4 \pm 3.0^{4.5.8.9}$	$31.3 \pm 28.4^{4.7.8.9}$	3.3 ± 4.7^{8}	3.3 ± 4.6^{8}	$1.6 \pm 1.6^{5.7}$	$3.1 \pm 2.5^{4.6.7.8.9}$
5:0 half court (4)	$271.8 \pm 156.4^{5.6.7.8.9}$	$3.6 \pm 2.0^{5.6.7.8.9}$	$3.5 \pm 7.6^{5.6.7.9}$	$1.4 \pm 2.4^{6.7}$	$1.5 \pm 2.2^{6.7}$	$0.7 \pm 0.9^{6.7.8.9}$	$1.3 \pm 1.5^{5.7}$
5:5 1.5 courts (5)	$760.1 \pm 308.1^{6.7.8.9}$	$12.5 \pm 5.3^{6.7.8.9}$	$40.9 \pm 30.4^{7.8.9}$	3.8 ± 4.5^{8}	3.9 ± 4.7	2.9 ± 2.7	$3.4 \pm 3.1^{6.7.8.9}$
5:5 2+ courts (6)	521.3 ± 352.8^{8}	8.4 ± 5.8^{8}	32.3 ± 27.0^{8}	$5.6 \pm 6.6^{8.9}$	$5.5 \pm 6.0^{8.9}$	1.4 ± 1.5^{8}	1.7 ± 1.9
5:5 Full court (7)	$572.1 \pm 257.8^{8.9}$	$9.1 \pm 4.2^{8.9}$	$26.8 \pm 24.6^{8.9}$	$3.5 \pm 5.1^{8.9}$	$3.5 \pm 5.2^{8.9}$	1.9 ± 1.8	2.2 ± 2.0^{8}
5:5 half court (8)	395.7 ± 175.7^{9}	6.3 ± 2.8^{9}	5.2 ± 11.7^{9}	1.8 ± 3.1	1.8 ± 3.1	1.4 ± 1.4	1.7 ± 1.6
5:5 live game (9)	460.2 ± 181.8	7.5 ± 3.0	21.2 ± 20.2	2.4 ± 4.2	2.5 ± 4.3	1.6 ± 1.6	1.9 ± 1.7

Note: Media ± SD; HI ACC, High acceleration; HI DECC, High Deceleration, HI JUMP, High Jump, HI LAND, High Land; HSR, High Speed Running; m, meters; n, numbers, PL, Player Load. Numbers in superscripts indicate Bonferroni Post Hoc p < .05

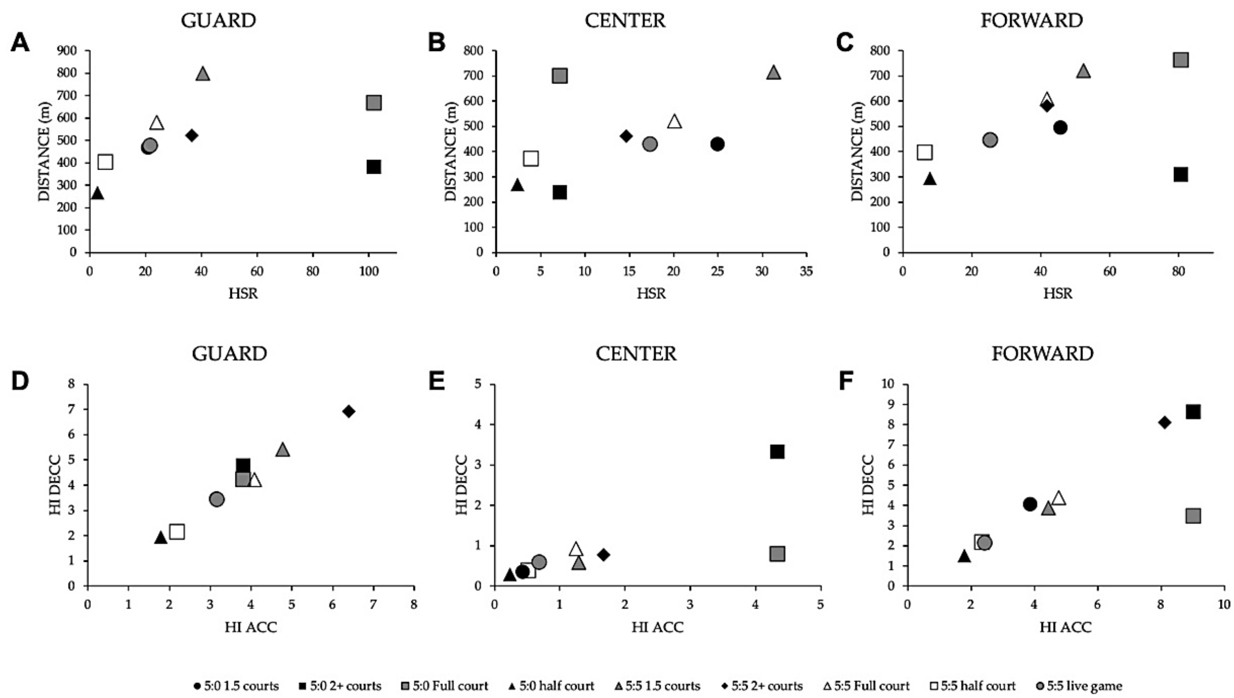
Table 2. Differences between basketball drills and positions.

Drill	Distance (m)			PL			HSR			HI ACC			HI DECC			HI JUMP			HI LAND		
	C	F	G	C	F	G	C	F	G	C	F	G	C	F	G	C	F	G	C	F	G
5:0 1.5 courts (1)	432.5 ± 131.6	495.5 ± 213.7	468.7 ± 161.2	6.9 ± 2.0	6.3 ± 2.4	7.2 ± 2.4	24.9 ± 24.0	$45.5 \pm 34.5^{4.8}$	$20.8 \pm 21.1^{2.4.5.8}$	0.4 ± 0.8	3.9 ± 3.7	3.1 ± 3.6	0.4 ± 0.6	4.1 ± 3.7	3.5 ± 4.7	1.6 ± 1.3	1.5 ± 0.9	$1.1 \pm 1.2^{5.7}$	2.6 ± 1.9	1.5 ± 1.0	2.5 ± 2.3
5:0 2+ courts (2)	240.2 ± 47.7	311.2 ± 60.0	383.6 ± 54.9	3.6 ± 0.8	3.7 ± 0.8	5.3 ± 0.8	**$7.1 \pm 1.0^{CF\ CG}$**	**$80.4 \pm 21.5^{4.8.9}$**	**$101.7 \pm 49.4^{3.4.5.6.7.8.9}$**	4.3 ± 1.5	9.0 ± 2.7	3.8 ± 2.2	3.3 ± 1.2	8.7 ± 3.8	4.8 ± 3.7	1.7 ± 1.5	1.3 ± 0.6	1.4 ± 1.5	1.3 ± 1.2	1.3 ± 1.2	1.6 ± 1.3
5:0 Full court (3)	703.2 ± 214.6	764.0 ± 269.0	670.8 ± 208.6	9.7 ± 2.9	9.0 ± 3.2	9.5 ± 3.0	**$29.1 \pm 33.9^{4.8\ CF}$**	**$54.2 \pm 25.9^{4.8.9\ FG}$**	**$23.9 \pm 21.9^{4.5.8}$**	0.9 ± 1.8	4.0 ± 4.2	4.0 ± 5.3	0.8 ± 1.6	3.5 ± 4.3	4.2 ± 5.2	1.6 ± 1.8	1.9 ± 2.0	$1.5 \pm 1.4^{5.7}$	3.0 ± 2.5	2.8 ± 2.7	3.3 ± 2.5
5:0 half court (4)	268.5 ± 173.8	294.9 ± 149.1	266.0 ± 153.3	3.7 ± 2.3	3.1 ± 1.3	3.7 ± 2.0	2.4 ± 6.0^{5}	$7.9 \pm 11.4^{5.6.7}$	$2.6 \pm 6.4^{5.6.7.9}$	0.2 ± 0.8	1.8 ± 2.5	1.8 ± 2.7	0.3 ± 0.9	1.5 ± 2.3	2.0 ± 2.3	0.8 ± 0.8	1.0 ± 0.9	$0.6 \pm 0.9^{5.7.9}$	0.8 ± 0.8	1.0 ± 0.9	1.6 ± 1.9
5:5 1.5 courts (5)	716.7 ± 317.6	722.2 ± 286.2	797.5 ± 316.6	11.9 ± 5.8	11.0 ± 4.6	13.5 ± 5.4	31.3 ± 28.7^{8}	$52.4 \pm 29.7^{8.9}$	$40.4 \pm 30.5^{7.8.9}$	1.3 ± 1.7	4.4 ± 3.5	4.8 ± 5.3	0.6 ± 1.0	3.9 ± 2.7	5.4 ± 5.6	2.1 ± 2.1	2.8 ± 2.7	$3.4 \pm 2.8^{8.9}$	2.3 ± 1.7	2.4 ± 2.7	4.3 ± 3.6
5:5 2+ courts (6)	462.1 ± 358.5	581.0 ± 407.7	521.1 ± 337.5	7.8 ± 6.2	8.4 ± 6.4	8.8 ± 5.6	14.7 ± 21.5	41.7 ± 34.6^{8}	36.4 ± 22.1^{8}	1.7 ± 1.5	8.1 ± 8.6	6.4 ± 6.6	0.8 ± 1.0	7.3 ± 7.0	6.9 ± 5.9	0.6 ± 1.0	1.2 ± 1.2	1.9 ± 1.6	1.0 ± 1.1	1.4 ± 2.4	2.1 ± 2.0
5:5 Full court (7)	521.3 ± 235.1	608.2 ± 271.3	580.9 ± 259.7	8.5 ± 3.8	8.6 ± 4.0	9.6 ± 4.4	**$20.1 \pm 25.0^{8\ CF}$**	**$41.7 \pm 29.3^{8.9\ FG}$**	**24.1 ± 19.7^{8}**	1.3 ± 1.7	4.8 ± 5.4	4.1 ± 5.7	0.9 ± 1.5	4.4 ± 5.5	4.2 ± 5.8	**1.1 ± 1.3^{CG}**	**1.7 ± 1.6^{FG}**	**2.3 ± 2.0^{8}**	1.4 ± 1.4	1.6 ± 1.8	2.8 ± 2.2
5:5 half court (8)	374.1 ± 177.5	398.0 ± 180.2	403.7 ± 173.0	6.1 ± 2.9	8.6 ± 4.0	6.6 ± 2.8	3.8 ± 9.8^{9}	6.2 ± 12.1	5.4 ± 12.3^{9}	0.5 ± 1.1	2.3 ± 2.8	2.2 ± 3.6	0.4 ± 0.9	2.2 ± 3.0	2.2 ± 3.5	**0.9 ± 1.0^{CG}**	1.4 ± 1.5	**1.6 ± 1.5**	1.1 ± 1.3	1.6 ± 1.4	1.9 ± 1.7
5:5 live game (9)	432.0 ± 162.3	446.6 ± 193.3	479.1 ± 184.3	7.1 ± 2.7	6.8 ± 2.9	8.0 ± 3.1	17.3 ± 18.2	25.4 ± 21.7	21.4 ± 20.3	0.7 ± 1.2	2.4 ± 3.6	3.2 ± 5.0	0.6 ± 1.2	2.2 ± 3.6	3.5 ± 5.2	**0.9 ± 1.0^{CG}**	1.3 ± 1.5	**2.0 ± 1.7**	1.4 ± 1.3	1.4 ± 1.3	2.3 ± 1.9

Note. *Note: Media ± SD; HI ACC, High acceleration; HI DECC, High Deceleration, HI JUMP, High Jump, HI LAND, High Land; HSR, High Speed Running; m, meters; n, numbers, PL, Player Load. C, Center; F, Forward; G, Guard. Numbers and letters in superscripts indicate Bonferroni Post Hoc p < .05.*

Significant differences in HI ACC and HI DEC were found between CF (0.9 ± 1.5 vs. 3.5 ± 4.4 for HI ACC; 0.7 ± 1.3 vs. 3.2 ± 4.3 for HI DEC) and CG (0.9 ± 1.5 vs. 3.3 ± 4.9 for HI ACC; 0.7 ± 1.3 vs. 3.5 ± 4.9 for HI DEC). For HI JUMP, differences were observed for CG (1.1 ± 1.3 vs. 1.9 ± 1.8), while for HI LAND, differences were found between CG (1.5 ± 1.6 vs. 2.5 ± 2.2) and FG (1.7 ± 1.8 vs. 2.5 ± 2.2). When analysing differences between positions and drills, no differences were observed for TD, PL, HI ACC, and HI DEC (Table 2).

Differences were found in HSR for the following scenarios: 5vs0 2+ courts for CF (7.1 ± 1.0 vs. 80.4 ± 21.5) and CG (7.1 ± 1.0 vs. 101.7 ± 49.4), 5v0 full court CF (29.1 ± 33.9 vs. 54.2 ± 25.9) and FG (54.2 ± 25.9 vs. 23.9 ± 21.9), and 5v5 full court: CF (20.1 ± 25.0 vs. 41.7 ± 29.3) and CG (41.7 ± 29.3 vs. 24.1 ± 19.7). Positional differences for TD and HSR, HI ACC and HI DEC are shown in Figure 2.



Note: HI ACC-High intensity acceleration; HI DEC- High-intensity deceleration, HSR- High-Speed Running; m, meters.

Figure 2. Comparison of external load between GBD and playing positions.

DISCUSSION

In our study, we first aimed to identify the most commonly used GBD formats in professional basketball during the competitive season. The prevalence of 5v5 and 5v0 GBD is consistent with expectations, indicating a strong emphasis on game preparation during this period (Schelling & Torres-Ronda, 2013). Previous research conducted during the preseason revealed that GBD involving opposition accounted for 38.3% of all tasks, while 61.7% were GBD without opposition (Calle et al., 2025). During the preseason, the primary objective is to enhance players' technical skills and conditioning, which guides the approach to training tasks (Calle et al., 2025). In contrast, in-season GBD involving opposition offer players valuable opportunities to engage in specific, realistic training scenarios (Schelling & Torres-Ronda, 2013).

When examining external load, TD was found to be lowest in half-court GBD and highest in full-court 5v5 (Vazquez-Guerrero et al., 2020). However, in basketball, the intensity of the distance covered seems to be more important, as elite players reach higher velocities than non-elite players (Petway et al., 2020). Therefore, in HSR, the highest values were found in 5v0 GBD with two courts, as the lack of opposition allows players to perform pre-planned movements at higher intensities (Sansone et al., 2023). Additionally, increased court size provides opportunities for faster transitions, or coaches may emphasize a faster-paced game, consequently elevating the speed of play. Introducing this type of GBD, which increases the distance covered at high speed, can have a protective effect and reduce the risk of injury (Vazquez-Guerrero et al., 2020).

The 5v5 GBD on 1.5 courts also showed the highest values in PL and HI LAND, which is consistent with previous research (Gamonales et al., 2023; Vazquez-Guerrero et al., 2020). However, other studies have shown that drills such as 3v3 (Sampaio, 2009; Schelling & Torres, 2016), 2v2 (Conte et al., 2016), and 1v1 (Torres-Ronda et al., 2016) impose the highest physical load on players. Interestingly, these particular drills were not frequently utilized during the competitive season by the team in this study. This could be attributed to the coach's emphasis on practicing team tactics, leading to a preference for GBD that prioritize team dynamics. Furthermore, when examining acceleration and deceleration, the highest number of HI ACC and HI DEC were observed in GBD using two or more courts, both with and without opposition. These drills showed higher values compared to half-court GBD, where the larger court size allows players to reach higher velocities, which may significantly influence HI ACC and HI DEC demands (Vazquez-Guerrero et al., 2020). This information is crucial as the acceleration and deceleration demands are higher in games than in training (Petway et al., 2020). By using appropriate GBD with a higher frequency of HI ACC and HI DEC, we prepare players more effectively for the physical demands of the game (Feu et al., 2023; Petway et al., 2020). An intriguing finding is that 5v5 live games did not exhibit higher loads compared to other 5v5 GBD played on a full court. This contrasts with the findings of Svilar et al. (Svilar et al., 2019), where non-stoppage 5v5 GBD showed higher values in terms of total decelerations, PL per minute, accelerations, and changes of direction compared to regular stoppage 5v5 drills. The lower values observed in live games may be attributed to the continuous nature of play, which can induce fatigue and limit players' ability to perform high-intensity actions (Conte et al., 2015).

When examining positional differences, no significant differences were observed in TD. For HSR, the highest values were recorded for forwards, followed by guards, and then centers. This can be explained by their style of play and their preparedness for the most demanding scenarios (García et al., 2020). In terms of PL, the highest values were found in guards, with no significant difference compared to centers. Centers exhibit high PL values due to their increased internal load, which is a result of inside play characterized by frequent contact and jumps (Calle et al., 2025). However, in our study, guards recorded the highest PL values compared to forwards, which may be attributed to their increased frequency of accelerations and decelerations (Dalen et al., 2016; Portes, 2019). For HI ACC and decelerations HI DECC, centers showed the lowest values, while forwards displayed the highest HI ACC and guards recorded the highest HI DECC, with no significant differences between these positions. The explanation for guards may lie in the technical aspects of the game and specific situations, whereas forwards, as previously mentioned, achieve higher speeds during training (Vázquez-Guerrero et al., 2018). It seems that both positions require more high-intensity actions than centers (Svilar, positional differences). Furthermore, guards exhibited the highest values for HI JUMP and high-intensity landings (HI LAND) compared to other positions, these types of actions often occur during offensive plays in basketball (Svilar et al., 2018). However, when examining specific GBD and positional differences, no differences were found for TD, PL, HI ACC, HI DECC, and HI LAND. Differences were identified in HSR during 5v0 on two courts for guards and 5v0 full-court and 5v5 full-court drills for forwards which highlights the importance of larger court sizes in facilitating higher velocities (Vázquez-Guerrero et al., 2018). For HI JUMP, differences were observed in 5v5 full-court, half-court, and live games for guards. Therefore, monitoring these variables closely during training sessions and games is crucial for effective player workload management. Individualizing training based on position is essential to replicate the demands of games (Vázquez-Guerrero et al., 2018).

While this study has provided valuable insights into the understanding of GBD in professional basketball, it is important to acknowledge certain limitations. First, the total training load includes both external and internal load, and the reliance on only external load data limits our ability to draw conclusions about the training responses and adaptations in professional players (Portes, 2019; Scanlan et al., 2014). Another limitation is the lack of data from official games. In the Spanish basketball leagues during the season 2022-2023, GPS devices are not permitted during official games, which restricts our understanding of the actual load experienced in these games. Having data from official games would help establish a clearer relationship between GBD and game demands. Additionally, a final limitation is that the study was based on data from a single professional team and only covered the final part of the season, which may limit the generalizability of the findings.

CONCLUSION

This study offers valuable insights into the external load experienced during GBD in professional basketball during the competitive season. The findings highlight the prevalence of 5v5 and 5v0 GBD, emphasizing game preparation as a core focus during this period. The external load, particularly in terms of TD, HSR, and acceleration/deceleration metrics, varies across different GBD formats and positional roles. Larger court sizes and drills with opposition often lead to higher physical demands, suggesting their importance for replicating game scenarios. Notably, the study found no significant differences in TD across positions but observed positional variations in high-intensity actions like acceleration and deceleration and HSR.

Future research should incorporate both external and internal load measures and include data from official games to further refine our understanding of how GBD impact player performance and adaptation in professional basketball. Monitoring and individualizing training load based on positional demands will be crucial for optimizing player performance and reducing injury risk.

AUTHOR CONTRIBUTIONS

Research concept and study design, R.M.N, and N.D.; Literature review, N.D., A.M and C.S.; Data Collection, N.D., R.M.N. and G.M. Data analysis and interpretation, A.M., N.D. Statistical analysis A.M. and G.M. Writing of manuscript, N.D.; Review and Editing N.D.; R.M.N and C.S.. All authors have read and agreed to the published version of the article.

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ORIGINAL ARTICLE

Comparative study of cross-country skiing on grip and skin skis

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ABSTRACT

The technology of cross-country skis for classic running is constantly evolving in the areas of ski construction or materials for ski construction. A study was focused to compare kinematic and kinetic parameters on grip and non-wax skis. Two groups of cross-country skiers participated in the with different skills quality. Kinematic and kinetic parameters of diagonal stride were observed: times of step cycle and phases, average and maximum pressure values of cycle phases. Pressure insole system was used for data collection. The Cohen size coefficient d was used. Differences between group of large effect size were found both on the flat and uphill for skiing on both types of skis (d = 0.82 - 17.26). Technically better skier showed minimal difference between skiing on both types of skis. For recreational skiers were found more differences on the uphill. Differences correspond to quality of movement patterns and ability of skiers to apply more efficiently technique on different types of skis on different type of terrain.
Keywords: Biomechanics, Ski base, Kinematics, Kinetics.

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INTRODUCTION

The technology of cross-country skis is constantly improving, and developments are being made in the areas of ski construction, materials, the ski base, as well as in new grip or gliding waxes. Thanks to these developments, skis for classical skiing, primarily for diagonal stride, have been enhanced over the last 50 years or so with a number of developments designed to facilitate waxing for recreational skiing and touring, and to improve the gliding and take-off characteristics in racing skis (Breitschädel, 2007). The evolution of cross-country skis, improving their basic properties, has been documented in many studies (e.g. Pellegrini, et al., 2018), using a large number of sophisticated devices and technologies. Hottenrot and Urban (2004) reported that technological development (66%) has had a greater contribution to performance improvement in cross-country skiing over the last 50 years or so than the actual improvement in athletes' performance (34%). This means that technology still has a lot to say in improving performance in cross-country skiing. Sintered thermoplastics have become the standard material for the ski base, which has significantly reduced the coefficient of friction (Breitschädel et al., 2010). Currently, elite skiers use 10-15 types of ski bases with specific properties for different snow conditions (Pellegrini et al., 2018). In recent years, a considerable amount of technological development has been devoted to the accurate characterization of friction in skiing, both in gliding and take-off (Breitschädel et al., 2010; Budde and Himes, 2017). The result of these efforts to improve the quality of cross-country skis for the classical technique became evident in the early 1970s, when the first skis with plastic ski bases began to be produced. Further opportunities arose to test and produce new types of ski bases which did not need grip wax for skiing up a slope, as these ski bases were fitted with so-called scales.

In the 1980s, so-called microstructure technology was developed for ski racing, which meant solving the problem of high-quality take-off in a climb without grip waxes with certain types of snow and climatic conditions and is still used in racing today. Since the beginning of the 21st century, Peltonen has been producing skis with a nanostructure on the ski base that is a form of non-waxing ski with good glide and take-off properties. In the last 6-7 years, another type of classical ski has emerged that does not need grip waxes but still has excellent take-off capabilities on all types of snow. These are the so-called skin skis, which have strips of fabric with hair (mohair) built into the take-off chamber of the ski base. Mohair is oriented in the direction of gliding and increases friction during take-off. This technology also provides a relatively good glide and is currently a very popular type of ski. This is the type of ski that is mainly used by recreational skiers who don't want to deal with grip waxes. Under certain conditions, this ski can also become a training ski for competitive cross-country skiers if waxing with grip waxes is a problem. It is used most in youth age categories. In race skiing, these skis are sometimes used under specific conditions, when waxing is a problem (high humidity, temperature around 0°C, smooth surface on the trail), under which they allow a good take-off and glide. Of course, the development of waxed skis has continued, and quite rapidly due to new technologies in ski construction, slide material and grip waxes (Swaren et al., 2014; Budde and Himes, 2017, Pellegrini et al., 2018).

Skin skis are used in diagonal stride or in double poling with kick. A number of studies have been carried out to describe the classical cross-country skiing technique from different perspectives: kinematic, kinetic, physiological, and muscle activity (Komi, 1987; Komi and Norman, 1987; Bilodeau et al., 1996; Smith et al., 1990; Bellizzi et al., 1998; Nilsson et al., 2004; Holmberg et al.,2005; Lindiger et al., 2009; Korvas, 2009, 2011; Mikkola et al. 2013; Andersson et al. 2014; Zoppirolli et al., 2015; Marsland et al., 2017; Pellegrini et al., 2022). From a locomotor point of view, diagonal stride is a quadrupedal activity in which forces are generated in the direction of movement by both the lower and upper limbs. The legs are the main contributors to the motor force production in diagonal stride. According to Bellizi et al., (1998), skiers generate 69% of their forward energy with the lower limbs, and 31% with the arms during diagonal stride at different speeds. The step cycle in diagonal stride is divided into the take-off, gliding and swing phases. Throughout the entire step cycle of diagonal stride, it is characteristic to transfer most of the weight to the front foot so that in the basic stance the skier reaches a position with the centre of gravity over the front foot and can perform all phases of the step cycle dynamically. The basis of propulsive leg force generation is to stop the ski and perform a dynamic take-off backwards (Nillsson et al., 2004; Lindinger et al., 2009). Diagonal stride is used on both flat ground and a slope, depending on the ability of the skier. Kinematic and kinetic analysis of the cross-country skier's movement are now standard tools in studies focusing on skiing technique at all ages and performance levels. Currently, these studies are conducted in the field under standard conditions and also in the laboratory on roller skis (Nilsson at al., 2004, Lindinger at al., 2009, Zoppiroli at al., 2020, Pellegrini at al., 2022).

Kinematic characteristics during cross-country skiing are most often investigated using 3D or 2D kinematic analysis. The most studied kinematic parameters are temporal. Lindinger (2009) determined that the step cycle averaged 1.21 sec in a group of high-quality skiers, with the contact phase with the snow averaging 0.74 sec (61.2%) and the swing phase averaging 0.47 sec (38.8%). Komi (1987) found a take-off time between 0.1 and 0.25 sec in high-quality skiers. Pellegrini et al. (2013) found that the step cycle time in high-quality skiers is 1.05 sec, the swing phase takes 41% of the cycle time, the take-off time is 0.21% and gliding 38%. Kinetic parameters were measured first using force platforms placed under the snow or force plates placed under the bindings (Rusko, 2003, Vähäsöyrinki at al., 2005). More recent research has used pressure insoles, which are easier for research, more mobile and more operational, however they have their limitations, as they only measure perpendicular pressure on the ski track (Lindinger et al., 2009, Korvas, 2011, Barnett et al., 2021, Pellegrini et al., 2022,). The values of the force under the skis during take-off have been investigated, e.g. by Moxnes and Hausken (2009), who found average values of around 1700 N on flat ground for hobby skiers, values of 2 – 3 mBW on a slope for an experienced skier, and in the range of 1.2 - 1.8 mBW for an average skier. Komi & Norman (1987) found take-off values between 1.5 mBW for skiing on flat to 3 mBW for skiing up a steep slope. Andersson (2014) tested skiers on roller skis who achieved an average value during take-off of about 2 mBW, and the value increased with higher speed. Lindinger et al. (2009) tested high-performance skiers and reported values during take-off in the range of 2-3 mBW.

A comparative study of cross-country skiing technique was carried out with two groups of skiers. The aim of the study was to compare selected kinematic and kinetic parameters while skiing on skin and grip skis, at the same running speed, in two technically different groups of cross-country skiers.

Research question: what will be the differences in selected kinematic and kinetic parameters during diagonal stride on grip and skin skis between quality and recreational skiers.

MATERIALS AND METHODS

Participants: ten cross-country skiers voluntarily participated in the study and were divided into two groups according to the quality of their diagonal stride technique. The first group (n = 5) consisted of skiers with good diagonal stride technique (established movement patterns). The second group were recreational cross-country skiers (n = 5), who demonstrated a lower quality of running technique (common deficiencies in the technique such as double support stance during the gliding phase in diagonal stride, insufficient range of arm movement during poling, and large vertical movement of the centre of gravity etc.). All participants were in good physical condition, which allowed multiple repetitions of the measured sections to be completed at the desired speed.

All participants signed an informed consent form prior to the start of the measurements and could voluntarily leave the research program during the experiment. The experimental protocol and all methods used in the study were approved by the ethics committee of the Centre for Sports Activities, Brno University of Technology.

Table 1. Characteristics of the groups of skiers.

Group	Age	Height	Weight
Skiers with good technique quality, n = 5	40±7	179±6	80± 6
Skiers with technical deficiencies, n = 5	22±2	181± 5	79±7

Measures

Prior to the start of the test, participants completed a standard warm-up process, which included practice of the speeds required in the test. The test area was very well prepared, the measurements were carried out on two well prepared sections of the racetrack. The first section was a 150-m-long flat, and the second was a 90-m-long slope with an average angle of 6°. The participants completed each section 3 times. For the flat run, the speed was set at 12 km/h, and for the uphill run at 11 km/h. Each participant completed the test on the flat and uphill sections on both types of skis three times. The lower speeds were set due to the fact that a group of recreational skiers also comfortably reached the test speed. The speed was controlled using a speedometer. There was sufficient time to have a rest between each section, at which time the pressure insoles were recalibrated for the next test.

For the measurements, each participant used performance-type grip and skin skis for classical style, which guaranteed good ski quality. The preparation of the skis corresponded to the climatic conditions. The tests were performed on natural relatively new snow, air temperature - 10°C, snow temperature - 5.2 C. Due to the good snow and climatic conditions, the grip skis of all participants could be prepared for take-off with the same wax, the only difference being the size of the grip wax layer, which corresponded to the take-off quality of the participants. The skin skis were treated according to the manufacturer's recommendations, a special cleaner was used for the skin. The gliding part of the skis were professionally prepared in the same way as the wax skis.

Procedures

For the collection of selected kinetic and kinematic data of the movement cycle, the Medilogic mobile pressure insole system (Medilogic, Germany) was used, which evaluates the pressures under the foot, from which both the time of the movement cycle and its individual phases can be derived on a time axis. The vertical pressure of the foot on the ski was recorded with the help of pressure insoles that each incorporated 100-190 pressure sensors regularly distributed over their entire surface. The recording was performed at a frequency of 100 Hz using special software from Medilogic. Calibration of the shoe insoles was performed before each measurement according to the company's manual. Sufficient accuracy of the measurements using the pressure insole was confirmed by the studies of Koch et al., (2016), Oerbekke et al., (2016), and Seiberl et al., (2018). All measured sections of the participants were video-recorded and used for expert evaluation of the running quality, to select the best section for data processing.

We monitored basic parameters of step cycle: the durations of each phase and of the entire step cycle, the percentages of each phase of the cycle, and the average and maximum pressure values of each phase. The step cycle of a single ski in diagonal stride was defined from the first touch of the ski to the snow track after finishing the swing phase, through the gliding phase, take-off and swing phases, to the next touch of the snow track by the same ski.

Analysis

With the help of the specific algorithm, very precisely defined the start and end of the skier's step cycle and each phase from the changes in the pressure on the insoles. The raw data were processed using our own algorithms developed in MATLAB version R2022, and numerical and graphical outputs of the average cycle values were produced. Of the measured sections, the one with the best quality was always selected for data processing. From the best test, the 30 consecutive step cycles that were visually free of coordination defects were selected for the flat and 20 for skiing on the slope.

Descriptive statistics were used and included mean, standard deviation and percentages. The Shapiro-Wilk test was used to test the normality of the data. The Cohen`s d effect size was calculated as an indicator of the magnitude of the effect, with d considered a small effect if $d = 0.2 - 0.50$, a medium effect if $d = 0.5 - 0.80$, and a large effect if $d \geq 0.8$

RESULTS

The results of the selected parameters of skiing on the flat on grip and skin skis are presented in Tables 2 and 3 for both groups.

Table 2. Kinematic and kinetic values of Group A and B during skiing on the flat on grip skis.

Group A					Group B				
Temporal parameters of step cycle (sec)					**Temporal parameters of step cycle (sec)**				
Phase	Swing	Gliding	Take-off	Step cycle	Phase	Swing	Gliding	Take-off	Step cycle
M	0.57	0.65	0.25	I.47	M	0.35	0.4	0.29	1.04
SD	0.09	0.06	0.05	0.21	SD	0.09	0.07	0.06	0.05
Relative values of step cycle (%)					**Relative values of step cycle (%)**				
M	38.8	44.2	17.0		M	33.9	38.2	29.9	
SD	2.9	2.6	0.8		SD	I.39	1.5	0.1	
Pressure values on insole (N/cm²)					**Pressure values on insole (N/cm²)**				
	Gliding	Take-off average	Take-off max			Gliding	Take-off average	Take-off max	
M	4.22	6.19	9.19		M	3.04	5.05	7.68	
SD	1.16	1.58	2.16		SD	0.41	1.56	2.37	

Table 3. Kinematic and kinetic values of Group A and B during skiing on the flat on skin skis.

Group A					Group B				
Temporal parameters of step cycle (sec)					**Temporal parameters of step cycle (sec)**				
Phase	Swing	Gliding	Take-off	Step cycle	Phase	Swing	Gliding	Take-off	Step cycle
M	0.59	0.65	0.26	1.49	M	0.33	0.41	0.32	1.05
SD	0.07	0.07	0.05	0.38	SD	0.08	0.11	0.08	0.9
Relative values of step cycle (%)					**Relative values of step cycle (%)**				
M	39.7	43.2	17.3		M	33.9	38.7	30.4	
SD	4.5	4.9	1.1		SD	0.88	0.32	2.1	
Pressure values on insole (N/cm²)					**Pressure values on insole (N/cm²)**				
	Gliding	Take-off average	Take-off max			Gliding	Take-off average	Take-off max	
M	4.23	6.26	9.32		M	3.09	4.69	7.41	
SD	1.42	1.92	2.89		SD	0.61	1.49	2.05	

For the absolute values of the selected temporal parameters for gr. A, only small differences in effect size were found between skiing on both types of skis (d = 0.01 - 0.21). For the relative temporal values, the differences were found out also a small effect size for the swing and take-off (d = 0.21 and d = 0.28, respectively) and for the gliding there was a large effect size (d = 1.85). The difference for all observed phases of the step cycle had a small effect for the technically better skiers only (d = 0.01 - 0.05).

In group B, difference of small effect size were found for the absolute kinematic parameters such as the swing and gliding, as well as the step cycle (d = 0.11 - 0.19). Only for the take-off was there a large effect size (d = 2.02) for a longer time on the skin ski. In relative values, large effects size were found for the take-off and swing (d = 5.27; d = 2.30, respectively) with longer time for the swing and shorter one for take-off on the skin ski. For gliding, there was a small difference in effect size (d = 0.42). The differences in pressure values during skiing on both types of skis had a small effect for the gliding and for the maximum pressure value during take-off (d = 0.11; d = 0.24, respectively). The mean value of pressure in the take-off was found as medium-sized effect (d = 0.76), and this take-off pressure was found to be higher on grip skis.

The results of the selected parameters during uphill skiing on grip and skin skis are presented in Tables 4 and 5 for both groups.

Table 4. Kinematic and kinetic values of Group A and B during skiing on the uphill on grip skis.

Group A					Group B				
Temporal parameters of step cycle (sec)					**Temporal parameters of step cycle (sec)**				
Phase	Swing	Gliding	Take-off	Step cycle	Phase	Swing	Gliding	Take-off	Step cycle
M	0.55	0.56	0.30	1.41	M	0.33	0.30	0.31	0.94
SD	0.09	0.08	0.05	0.08	SD	0.05	0.08	0.07	0.06
Relative values of step cycle (%)					**Relative values of step cycle (%)**				
M	39.9	40.8	21.3		M	35.1	31.9	33.0	
SD	3.8	3.8	1.2		SD	0.14	0.87	0.92	
Pressure values on insole (N/cm²)					**Pressure values on insole (N/cm²)**				
	Gliding	Take-off average	Take-off max			Gliding	Take-off average	Take-off max	
M	3.69	6.65	9.71		M	2.21	4.36	7.3	
SD	0.67	1.37	2.78		SD	0.87	1.50	2.53	

Table 5. Kinematic and kinetic values of Group A and B during skiing on the uphill on skin skis.

Group A					Group B				
Temporal parameters of step cycle (sec)					**Temporal parameters of step cycle (sec)**				
Phase	Swing	Gliding	Take-off	Step cycle	Phase	Swing	Gliding	Take-off	Step cycle
M	0.55	0.63	0.27	1.45	M	0.30	0.33	0.31	0.94
SD	0.04	0.05	0.04	0.05	SD	0.06	0.09	0.08	0.07
Relative values of step cycle (%)					**Relative values of step cycle (%)**				
M	37.6	43.6	18.8		M	31.9	35.1	33.0	
SD	1.7	2.6	0.6		SD	2.3	1.9	2.1	
Pressure values on insole (N/cm²)					**Pressure values on insole (N/cm²)**				
	Gliding	Take-off average	Take-off max			Gliding	Take-off average	Take-off max	
M	4.09	6.46	9.63		M	2.9	4.75	7.59	
SD	0.54	1.67	2.15		SD	0.71	1.42	2.07	

When skiing on an uphill, which is a more demanding terrain for performing of skiing technique, some differences were found in group A for important absolute and relative time parameters. For absolute values of selected temporal parameters, a longer gliding time was found on skin skis with large-sized effect (d = 0.80) and the take-off was performed in a shorter time on skin skis with a large effect (d = 1.0). The step cycle time was longer on skin skis with a medium-sized effect (d = 0.68). For relative values, were found out a large effect for the gliding and take-off (d = 0.91 and d = 2.00, respectively). The swing was found to have a small effect (d = 0.4). The differences for the mean and maximum values of the take-off pressure were minimal, (d = 0.01, d = 0.03, respectively). The gliding phase was found longer on skin skis with a medium-sized effect (d = 0.57).

For the skiers in group B, only small effects were found for the absolute time parameters of all observed variables (d = 0.00 - 0.45). However, in relative values, this meant a large effect for the swing (d = 1.07), which lasted longer on the grip skis, and the gliding phase was longer on the skin skis (d = 0.75). For take-off was found a large effect (d =1.11) with longer time on grip skis . The difference in the pressure for group B during gliding and the mean pressure during take-off had a medium-sized effect (d = 0.78 and d = 0.77 respectively) with a larger value always being found on the skin skis. A small effect size was found for maximum take-off pressure (d = 0.27).

Comparison of the studied parameters between our groups when skiing on grip and skin skis
When comparing our two groups, a large effect can be observed for almost all parameters on the flat and on the uphill on both grip and skin skis. This means that the kinematic and kinetic characteristics of both groups are different on both grip and skin skis. All kinematic parameters were better in group A, a longer movement cycle and a longer glide and take-off, which are essential for good skiing technique. The differences between the two groups are shown in Tables 6 - 9.

Table 6. Cohen coefficient d for selected variables of skiing on flat on grip skis between Gr. A and Gr. B.

Absolute time values of step cycle		**Relative values of step cycle**		**Pressure values**	
Cohen d	Phase	Cohen d	Phase	Cohen d	Phase
2.21	Swing	2.15	Swing	1.1	Gliding
3.46	Gliding	2.55	Gliding	0.66	Mean take off
0.8	Take off	17.26	Take off	0.6	Max take off
4.54	Step cycle				

Table 7. Cohen coefficient d for selected variables of skiing on flat on skin skis between Gr. A and Gr. B.

Absolute time values of step cycle		**Relative values of step cycle**		**Pressure values**	
Cohen d	Phase	Cohen d	Phase	Cohen d	Phase
3.12	Swing	2.39	Swing	0.94	Gliding
2.35	Gliding	1.17	Gliding	0.82	Mean take off
0.83	Take off	4.95	Take off	6.63	Max take off
0.83	Step cycle				

The values for selected kinematic and kinetic parameters indicate mostly large differences in the time of all step cycle phases on the flat. Medium-sized effect was found between the groups when running on the grip skis for both mean and maximum pressure during take-off (d = 0.66; d = 0.60, respectively). In both cases, the recreational skiers generated less pressure during take-off than the skiers with better technique.

In the uphill skiing, mostly large effects were found between groups. The with two exceptions. For absolute time of take-off on the grip skis was found to have a small effect (d = 0.14). In absolute values, we found a medium effect size for the take-off time on the skin skis on uphill (d = 0.63), which was longer for the recreational skiers. All remaining kinematic and kinetic differences between the groups on both the grip and skin skis when skiing on flat or uphill were found to have large effects (d = 0.82 - 17.26).

Table 8. Cohen coefficient d for selected variables of skiing on uphill on grip skis between Gr. A and Gr. B.

Absolute time values of step cycle		**Relative values of step cycle**		**Pressure values**	
Cohen d	Phase	Cohen d	Phase	Cohen d	Phase
2.73	Swing	1.61	Swing	1.72	Gliding
2.99	Gliding	2.91	Gliding	1.31	Mean take off
0.14	Take off	9.96	Take off	0.82	Max take off
6.00	Step cycle				

Table 9. Cohen coefficient d for selected variables of skiing on uphill on skin skis between Gr. A and Gr. B.

Absolute time values of step cycle		**Relative values of step cycle**		**Pressure values**	
Cohen d	Phase	Cohen d	Phase	Cohen d	Phase
9.21	Swing	2.68	Swing	2.36	Gliding
3.72	Gliding	3.33	Gliding	1.00	Mean take off
0.63	Take off	8.62	Take off	0.87	Max take off
7.57	Step cycle				

DISCUSSION

The constant development of technology and new materials have enabled improvements to the construction of the ski, the quality of the means for preparing the ski (waxes, structures) and also the preparation of the tracks. All of these variables influences the performance of skiers (Hottenrot and Urban, 2004), and the biomechanical parameters by which we can characterize the quality of their movement (Rusko, 2003; Breitschädel et al., 2010; Budde and Himes, 2017; Pellegrini et al., 2018). If we compare the results of our groups on grip skis with other studies, the kinematic parameters for group A are similar to studies with high-quality skiers (e.g., Nillson et al., 2004; Lindinger et al., 2009; Pellegrini et al., 2020, 2022). Also, the take-off pressure values for this group after converting to force are similar to results which presented Komi (1987), Moxes and Hausken (2009), or Anderson et al. (2014). This confirms the possibility of objectively comparing the effect of the new technology in the group of higher-quality skiers (gr. A) and then comparing their results with the group of recreational skiers (gr. B). When comparing the results of selected kinematic parameters from the above-mentioned studies as well as the results of group A with the results of poorly skilled skiers (gr. B), a longer time of the take-off on the flat and on the uphill was found in our group B, which we consider to be important findings.

The remaining variables in group B had a higher variability in the results, but it was possible to prove, they too have large differences in technique compared to the better skiers, and we can conclude that they don't have a stable technique and automation of movement. It was assumed that quality movement skills would be evident in both kinematic and kinetic parameters. The differences between groups had large effects for skiing on wax and skin skis, with some exceptions on both flat ground and uphill. The small or medium-sized effect of take-off on the uphill on both wax and skin skis is more likely a result of low speed, at which skiers with good technique don't dynamically perform a take-off that is slow. During take-off on the flat, both groups generate a more similar pressure at the same speed (medium-sized effect). This is a consequence of the technically easier take-off. When skiing on the flat, group B takes more advantage of the skin ski during take-off, whereas for group A at low speed prevail automated movements without the need to adapt skills to new technology.

On the uphill, the differences between the groups again mostly had a large effect, but on both types of skis the absolute take-off time was more similar for both groups. This is a consequence of the need to reduce take-off time to be efficient. On the uphill, the skills of group B are also supported by technology that can compensate for the low quality of take-off and allow the skier to perform the necessary movement structure with a higher quality than the skier is capable of on grip skis.

In the intra-individual group evaluation of skiing on the grip and skin ski, the smallest differences were found for skiing in the flat, which is a technically and physically less demanding terrain, on which, at a low movement speed, even technically less capable skiers are closer to the movement structure performed by better skiers. When skiing on flat terrain, this is a moderately difficult movement structure with less force needed to influence spatiotemporal parameters. When comparing the results of skiing on grip and skin skis for both groups, we find the greatest number of small differences (similar, non-significant results) in absolute values of the time parameters when skiing on flat terrain, i.e., on simple, easy terrain, at low skiing speeds, and therefore at low load intensity. Here we did not find many significant kinematic or kinetic differences.

On flat ground, both groups had similar time for the step cycle on both skis, and also the proportion of each phase within the step cycle was similar for group A, with no significant differences, but no for gliding, what is logical. For group B, there was only a large difference in the take-off time, which was longer on the skin skis both in absolute and relative values. This is clearly a consequence of the effect of the new technology, which allows a longer take-off without technical problems such as the ski slipping backwards on grip skis and technology compensates the lack of take-off skills. We think this is logical, since in this case recreational skiers can perform a longer take-off without worrying about the ski slipping. This is a sought-after change in the movement pattern of the cycle, which is caused by the new technology, which allows technically less skilled skiers to perform the take-off more confidently. The skier can perform take-off for a longer time and more efficiently, and this change is reflected in the kinematic movement structure of the individual, because at the same time the swing phase of the second lower limb responds to this change and is significantly extended.

Time of take-off is an important variable that influences the quality of the skiers' technique, and on grip skis this corresponds to the quality of the snow conditions and the ability to produce a sufficient pressure for the resistance between the ski base and the snow track so that the ski does not slip backwards. Both groups performed a shorter take-off on the flat than on the uphill (absolute and relative time values) because there was no need to generate as much propulsive force at the lower speed and the take-off could be shorter, thus confirming both groups' ability to adapt their technique to the conditions created by the type of ski used for the take-off. The difference in gliding is of course due to the greater resistance of the skin skis, on which the skier covers a shorter distance during the step cycle on the skin skis and also in shorter time. However, quantifying the distance covered during the step cycle was not the aim of this study.

Advanced skiers with good technique apply more automated movement patterns when skiing on the flat on both types of skis, so from a kinematic point of view, the different ski type only has a minor effect on the step cycle. For technically better skiers, there is no difference on the flat when skiing on grip and skin skis, nor is there a difference in the value of pressure on the insoles, which is again consequence of low speed and low intensity of movement. In group B, when evaluating the values of take-off pressures, we already find a difference, which shows that even skiers with imperfect take-off on the grip skis can increase the pressure on the skin skis and perform a reliable and more dynamic take-off.

In uphill skiing, we already found more significant differences (medium-sized and large effects) for the different groups. Skiing in more challenging terrain is also more technically demanding, especially in terms of the correct execution of the take-off phase, where it is especially important to adapt the length and dynamics of the take-off to the angle of incline and the quality of the snow track (Rusko, 2003). On the uphill, there was a similarity in some absolute values of the time indicators for both groups (swing, gliding, step cycle). A logical justification can be found for the gliding and step cycle in group A, which are affected by the worse slipperiness of the ski. The shorter swing in group B is usually due to poorer technique, balance, longer gliding on both skis after putting the ski on the snow to early, these are a common deficiency of this kind of skiers. On the uphill, both groups already showed significant differences in relative values for the take-off time, which was shorter on the skin skis than on the wax skis. On the uphill, the correct technique is physically and technically more difficult. This was confirmed by the simpler and more confident carry out of the take-off on the skin skis. What we somewhat expected here is a longer time of take-off on grip skis for group B, with more variability and less quality of take-off. But this was not confirmed, these skiers performed the take-off both absolutely and relatively in a similar time. It means, they took advantage of the skin skis to perform a faster and more reliable take-off on the uphill.

On the uphill, the differences were also found in the group with better ski technique, and it is clear that there is also some effect of the new technology on the movement pattern in the take-off of the diagonal stride, but also subsequently in the gliding, which is affected by the worse mechanical properties of the skin ski base. In the take-off, this is a logical adaptation to speed and conditions, and if a firm take-off is made, it can result in a longer gliding. A medium effect size was found for longer absolute gliding time and a large effect for shorter take-off time on skin skis. These are logical differences, especially for gliding, which is influenced by the mechanical principles of the ski gliding on snow. Shortening of the take-off is also a result of experience based on a good feel for the ski's properties and adapting the take-off to the conditions. This suggests that under more technically demanding conditions, skiers with good technique will adapt the take-off to the new technology and take advantage of it to perform a fast dynamic take-off.

For group B, we found more differences in the take-off when skiing on the uphill. This is a group that has not yet automated the correct movement structures well. The relatively shorter take-off time suggests the advantages of a skin ski for this group under conditions that are problematic for the use of an appropriate grip wax. Group B skiers are therefore more confident on skin skis when performing a take-off on the uphill that can be more dynamic and faster. Extending the gliding was not anticipated but is possible when performing a firm take-off that generates more propulsive forces for longer gliding. It may also be the result of placing the ski on the snow too early at the end of the swing phase and performing a long glide on both skis, which is a common mistake in technically less skilled skiers. Of course, the take-off is also influenced by some other factors that negatively affect the technique of the run, such as changes in the position of the body and quality of movement coordination in changing terrain, changing snow and track quality, lower ability to quickly and accurately transfer the centre of gravity over the gliding ski, i.e. precise and dynamic movement in the medio-lateral direction, and also a lower level of specific strength, which are always found in less skilled skiers (e.g. Rusko, 2003, Hottenrot and Urban, 2004, Ilavský et al., 2023).

For both groups, there is a change in the temporal characteristics of the take-off on the uphill due to technology that facilitates the generation of propulsive forces in the direction of motion. This gives greater confidence to perform fast, dynamic motion, especially under problematic wax and take-off conditions. The shorter take-off time also corresponds with the better ability of skiers to use the ski's take-off properties, even in technically superior skiers, which is shorter in skin skis. The skier does not have to think more about the correctness and do the take-off dynamically in a shorter time. Thus, it is clear that more changes occur in more challenging terrain, where it is more difficult to apply a take-off technique that is appropriate to the needs of the moment.

When evaluating the pressures generated during gliding and take-off on grip skis in recreational skiers, we observe lower values than in higher quality skiers (gr. A) or even in other studies (e.g. Komi, 1987, Anderson et al., 2014). This is usually due to insufficient weight transfer to the loaded ski, gliding on both skis, poor take-off execution (length, dynamics), poorer quadrupedal coordination, lower levels of specific force required for a quality take-off, and the interplay of agonists and antagonists.

The differences in the values of pressure do not support the assumption that its value would change significantly during take-off on flat in group A. This change only occurred in the technically weaker skiers, who also took advantage of the reliable take-off to increase the take-off pressure, and thus to a more reliable take-off and creating greater propulsive force in the direction of movement. The differences in the values on the pressure insoles for both groups when skiing on the flat between the two types of skis were found to mostly have small effects, which is also a result of the low intensity of the movement due to the low speed in the test. We found a medium effect size for the difference in mean take-off pressure for group B, which indicates the ability to produce more pressure on the skin skis while ensuring a firm and secure take-off.

More differences were found for both take-off and gliding on the uphill, and these differences were mostly a medium-sized effect for both groups. With gliding, this is also due to the higher resistance of the ski when moving on the snow. More interesting were the differences that indicate changes in the pressure on the insole during take-off. These were only evident in group B with lower pressure values on the sensor on skin skis on flat and also on uphill skiing, while in group A the values for take-off were similar on both types of skis on terrain. This confirms the use of automated movement patterns in better skilled skiers and, on the other hand, the ability to take advantage of the new technology in group B, which manifests itself in a greater pressure on the skin ski during take-off on uphill skiing and lower than on grip skis on flat, where is take-off easier to perform. Thus, under standard snow conditions, skiing on both types of skis from the point of view of take-off pressure is more comparable in group A. In group B, there is a medium-sized difference in effect size for this parameter, which clearly confirms the simplification of take-off on the flat, which makes it possible to take-off with lower pressure without the ski slipping backwards. However, this should be taken into account in training, and practicing technique on skin skis should only be used under conditions where waxing is problematic. The consequence of inadequate use of skin skis can be in poor movement pattern of take-off on the grip skis.

CONCLUSIONS

Group A demonstrated similar kinematic values to skiers in other studies (Komi, 1987, Lindinger, 2009, etc.) for skiing on grip skis. On skin skis, they showed a somewhat steady movement pattern, although there were some differences, especially for the gliding and also on the uphill for the take-off.

For skiers with good technique, differences in selected kinematic and pressure parameters were minimal when comparing skiing on both types of skis on the flat. This was due to the quality of the automated movement skills/technique, which varies minimally on different types of skis under the same snow conditions, but they are able to adapt to the conditions. Only in relative gliding values are there logical differences due to the increased resistance of the ski. On the uphill, it is already possible to find differences in take-off, which is the main variable observed in skin skis, and it is clear that even the A group uses a firm take-off for its faster and more dynamic performance.

For the group of recreational skiers, we found out differences of medium and large effect size for kinematic variables on the flat and on the uphill, especially for take-off. For the pressure parameters, the effect of the new ski types is medium in size. This suggests an advantage to using a firmer take-off than on grip skis, which can be a technical problem for recreational skiers.

The differences between the groups were significant in almost all parameters, both on the flat and on the uphill. The differences between the groups were logical, and it is clear that the ability to use the existing skills of each skier, and their adaptation with respect to external conditions and ski type, is decisive.

From the results of group B, we conclude that from a methodological point of view, the use of skin skis in training should be approached with discretion and only under specific climatic and snow conditions, so as to develop a feel for both take-off and gliding as an important part of the XC skiing technique under different climatic and snow conditions.

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The contribution of the authors has been as follows in each of the sections: P. Korvas 40 %; T. Goldschmidt 20 %; O. Jaroš 20 %; J. Štastný 20 %.

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ORIGINAL ARTICLE

Neuromuscular activity differs between the inside and outside legs during bend sprinting

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ABSTRACT

This study aimed to clarify the characteristics of surface electromyograms during sprinting on a curved path. The participants were eighteen male track and field athletes including sprinters and hurdlers. Participants performed a 60-m sprint with maximal effort on straight and curved paths. Surface electromyogram signals were sampled from the biceps femoris, gluteus maximus, rectus femoris, vastus lateralis, medial head of gastrocnemius, and tibialis anterior, and kinematic variables and ground reaction forces were measured during sprinting. These variables were compared between straight and curved paths. Average rectified value of surface electromyograms for medial head of gastrocnemius in the inside leg on a curved path was greater than that on a straight path; however, there were no significant differences between the paths in the outside leg. In addition, there were no significant differences between paths. These results suggest that electromyographic strategies for performing curved sprinting with a large radius of curvature differ between the inside and outside legs and, that gastrocnemius muscle activity on inside leg contributes to force production during bend sprinting.

Keywords: Biomechanics, Sprint performance, Electromyography, Curved path.

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INTRODUCTION

It has been reported that the highest running speed that appears in the middle of a race greatly affects the performance of sprint events in athletics. (Hanon and Gajer,2009; Mackala, 2007). However, in 200 m and 400 m events, it is necessary to sprint on a curved path because of the design of the track and field stadium. That is, it is one of the tasks to acquire a high running speed on a curved path to improve the performance for 200 m and 400 m events.

To make curved sprinting possible, it is necessary to produce centripetal force; therefore, it is a general strategy to produce centripetal force by leaning the body toward the centre of curvature. It is generally accepted in previous studies that the running speed on curved paths tends to be slower than that on straight paths (Chang and Kram, 2007; Churchill et al., 2015; Churchill et al., 2016; Stoner and Ben-sira, 1979). Regarding the kinematics and ground reaction force during curved sprinting, there are reports of differences in the variables between the straight and curved paths in the frontal and sagittal planes (Churchill et al., 2015; Churchill et al., 2016) and only in the frontal plane (Alt et al., 2015; Hamill et al., 1987). There are a few reports on the characteristics of curved sprinting, and consistent knowledge has not yet been obtained.

Kinematic and kinetic characteristics during curved sprinting were reported by comparing movements on a straight path. However, only one report has investigated the surface electromyogram, which is one of the biomechanical characteristics. Smith et al. (2008) investigated the differences of the difference in lower limb muscle activities in inside and outside legs on straight and curved path with 5 m radius of curvature at 4.4 ms^{-1} and 5.4 ms^{-1} running speeds. The tibialis anterior muscle activity during the flight phase increased in the inner leg, and the tensor fasciae latae muscle during the flight phase and gluteus muscle during the running cycle increased in the outer leg on a curved path with increasing speed. However, there were no significant differences between straight and curved paths. The experimental setting mentioned in the previous study was slower and smaller in radius of curvature than conditions, such as sprinting events in athletics. Therefore, muscle activity during sprinting on a curved path shows characteristics different from those of the previous study. Many previous studies have reported the characteristics of surface electromyogram during sprinting on the straight path (Kuitunen et al., 2002; Mero and Komi, 1987; Nummela et al., 1994; Nummela et al., 1992; Slawinski et al.,2008), but it has been not clarified the characteristics on curved path. Centripetal force is added compared to sprinting on a straight path during sprinting on a curved path, so the total force exerted is greater. Therefore, we hypothesized that the surface electromyogram would also be greater during sprinting on a curved path, and that the areas affected would differ between the inside and outside leg.

This study aimed to clarify the characteristics of surface electromyograms during sprinting on curved paths, such as sprint events in athletes.

MATERIAL AND METHODS

Participants

Eighteen male track and field athletes (age 20 ± 1years, height 1.74 ± 0.06 m, weight 67.2 ± 4.9 kg) volunteered for this study. None of the participants reported musculoskeletal injuries at the time of testing. Approval to undertake the study was given by Japan Institute of Sports Sciences. Written informed consent was obtained from all the participants.

Measures

The trials involved 60 m sprint running on straight and curved paths. This experiment was conducted in a laboratory with all-weather pavement. The detrimental effects of curvature on running speed tend to be larger for smaller radii (Churchill et al., 2019; Greene, 1981; Quinn, 2009). The radius of curvature was 37.9 m, which corresponds to the most inside lane of a typical 400-m track. The participants performed 8 to 10 trials, two for each leg and path, during the same period. Between trials, participants rested for more than ten minutes to offset the effect of fatigue on running speed. The measurement section was 45 m from the start of both the paths.

Surface EMG signals were sampled from the biceps femoris (BF), gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), medial head of the gastrocnemius (MG), and tibialis anterior (TA) on the inside and outside legs based on a previous study (Mero and Komi, 1987). The skin surface was cleaned with alcohol and rubbed with sand. Surface Ag/AgCl electrodes (Blue Sensor; Ambu, Copenhagen, Denmark) were used as the recording electrodes and were placed on the longitudinal axis of each muscle at an interelectrode distance of 30 mm. Bipolar surface electrodes were placed on individual muscles, in accordance with previous studies (Delagi*, 1981;* Higashihara *et al., 2010*). Signals were recorded using a portable data logger system (dimensions 34 × 77 × 132 mm, mass 300 g, BioLog DL 5000, S & ME Inc., Tokyo, Japan) attached to the waist at a sampling frequency of 1000 Hz. Electrode wired sensors (FA-DL 140, S & ME Inc., Tokyo, Japan) with an amplification amplifier of 12 × 7 × 23 mm were attached to the electrode, and connected to the electrodes were secured with tape to avoid movement-induced artifacts. The entire leg was covered with underlap tape (U 70 F; Nichiban Co., Tokyo, Japan) to fix the electrode. The presence or absence of abnormalities on each electrode was confirmed using measurement analysis software (m-BioLog 2, S & ME Inc., Tokyo, Japan).

Reflective markers were placed on body landmarks based on plug-in gait protocols (Davis et al.,1991; Kadaba et al.,1990). Three-dimensional positional data of the markers were recorded using a motion capture system operating at 250 Hz with 15 infrared cameras (Vicon MX; Oxford Metrics Ltd., Oxford, UK). Two force plate systems (Type 9286 B, Kistler Inc., Winterthur, Switzerland) were used to sample the ground reaction force (GRF) data at 1000 Hz. The positional data and GRF data were synchronized using Vicon Nexus software (ver. 1.7.1, Oxford Metrics Ltd., Oxford, UK.). In this study, we used only two force plate systems. Therefore, the kinematic and GRF data for each leg were obtained from separate trials. The global coordinate system directions were set as the X-axis for the medial-lateral direction, the Y-axis for the anterior–posterior direction, and the Z-axis for the vertical direction. On a curved path, the global coordinate system is translated to a local coordinate system, in which the X-axis is defined as a radial-to-curved path, and the Y-axis is a tangential-to-curved path.

Procedures

The recorded electromyogram data were loaded into the aforementioned software, and the data on each electromyogram were obtained. The EMG data were filtered with a band-pass of 20–500 Hz and rectified. Average Rectified Value (ARV) was performed during the analyse running cycle. The running cycle was divided by defining the onset-offset point of the MG at foot contact. The mean value of three cycles in total, including before and after the measured section that stepped the force plate systems, was set as a representative value in each trial. The ARVs at each straight path was normalized to 100% and a relative value was calculated for each curved path.

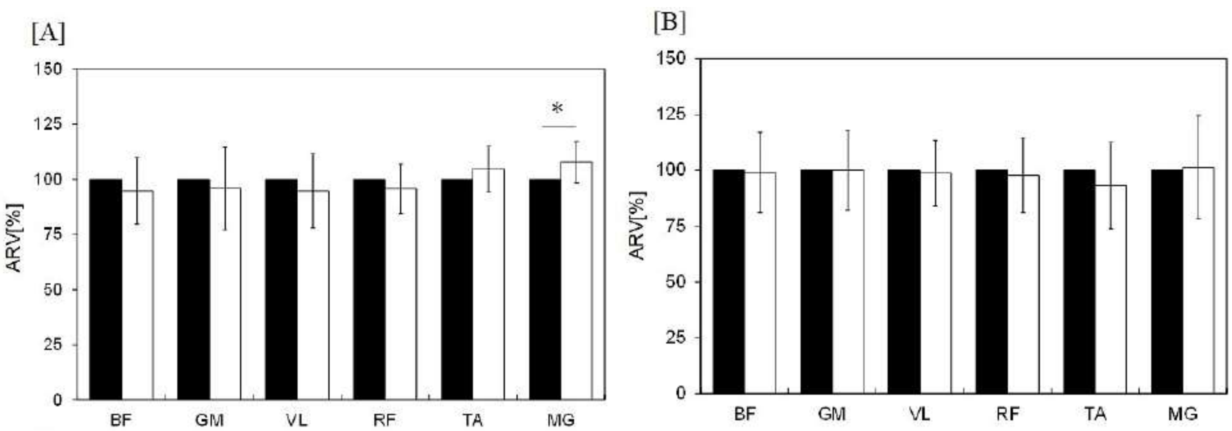
The Vicon Nexus software was used to reconstruct the positions of each reflective marker in a three-dimensional graphical environment. Each marker on the participant was labelled according to the body landmark to which it was attached or according to the cluster to which it belonged, based on the plug-in gait protocols. The positional data and GRF data were smoothed using a fourth-order Butterworth digital filter with cutoff frequencies of 12 and 50 Hz, respectively. The centre of gravity was calculated using body segment variables, which were based on Jensen's mathematical model for Japanese athletes (Ae, 1992). The lower-limb angle and angular velocity were calculated from the three-dimensional coordinate values. The spatiotemporal variables were calculated for the inside and outside steps on both paths. In accordance with previous studies (Churchill et al., 2015; Churchill et al., 2016; Stoner and Ben-sira, 1979), a right (outside) step was defined from outside foot touchdown to inside foot touchdown, and vice versa for a left (inside) step. The running speed for each path was calculated by averaging the running speeds of the inside and outside steps. Lower-limb movements in the sagittal plane during the stance phase were calculated for the inside and outside steps on both paths. The lower limb joint angles on foot touchdown and foot take-off, minimum knee and ankle joint angles, and maximum lower limb joint extension (plantarflexion) angular velocities were calculated. The maximum and minimum GRF and impulse for each coordinate were calculated for the inside and outside steps, respectively. The impulse of the anterior-posterior component is divided into eccentric and concentric phases (Mero and Komi, 1987). Kinematic, GRF, and EMG data of the fastest trial for each leg and path were used for detailed analyses. All data processing was performed using the MATLAB software (R2013a, The MathWorks Inc., Natick, MA, USA).

Statistical analysis

The Paired t-test was used to compare variables between the straight and curved paths for each leg. Statistical significance was set at $p < .05$. Cohen's d was used to describe the effect size (Cohen, 1992). All statistical analyses were performed using the IBM SPSS Statistics software (v. 22.0, SPSS Inc., Chicago, Illinois, USA).

RESULTS

Figure 1 shows that differences of the ARV in inside and outside each lower limb muscles on straight and curved path. ARV for MG in inside leg on curved path was greater than on straight path ($p = .03$, d = 0.82). However, there were no significant differences in the outside legs between paths. In addition, there were no significant differences between paths.



*Note. Values are presented as mean ± standard deviation (n = 18). * Significant difference between straight and curved paths (p < .05).*

Figure 1. Comparisons of ARVs in [A] inside and [B]outside legs between straight (black bar) and curved paths (white bar).

Table 1 shows the differences in the kinematic parameters in inside and outside the leg on straight and curved paths. The running speed on the curved path was slower than on the straight path (p < .01, d = 1.11). The mean percent difference of the running speed relative to straight path also was -3.10 % ± 1.51 (Range:-0.43 - -6.33%). There were no significant differences in the step frequency, stance time, or flight time for both legs between the paths. However, the step length (p < .01, d = 0.69) and flight distance (p < .01, d = 0.60) of the outer leg on the curved path were significantly shorter than those on the straight path. However, there were no significant differences in the step length and flight distance of the inside leg between paths. The minimum knee (p = .01, d = 0.52) and ankle (p = .02, d = 0.23) joint angles of the inside leg on the curved path were significantly smaller than those on the straight path; however, there was no significant difference in the outside leg. On the other hand, the knee joint angles at foot touchdown (p = .02, d = 0.44) and take-off (p < .01, d = 0.76) of the outside leg on the curved path were smaller and larger than those on the straight path, respectively, but there was no significant difference in the inside leg.

Table 1. Differences in the kinematic parameters in inside and outside the legs on straight and curved paths.

	Straight		**Curve**	
	Inside	Outside	Inside	Outside
Spatiotemporal variables				
Running Speeds [m/s]	9.47 ± 0.28		9.17 ± 0.26*	
Step length [m]	2.03 ± 0.14	2.01 ± 0.13	2.00 ± 0.12	1.91 ± 0.16*
Stance distance [m]	0.99 ± 0.06	0.98 ± 0.08	0.99 ± 0.08	0.97 ± 0.08
Flight distance [m]	1.04 ± 0.12	1.02 ± 0.10	1.02 ± 0.12	0.95 ± 0.13*
Step frequency [Hz]	4.73 ± 0.34	4.63 ± 0.34	4.65 ± 0.32	4.68 ± 0.33
Stance time [ms]	105.6 ± 8.0	105.6 ± 9.9	109.1 ± 10.0	107.1 ± 9.8
Flight time [ms]	106.9 ± 12.3	107.1 ± 9.8	106.8 ± 12.1	107.8 ± 9.9
Joint angle [deg]				
Hip joint extension-flexion angle at TD	132.2 ± 4.1	132.7 ± 5.2	131.3 ± 3.2	131.0 ± 4.1
Knee joint angle at TD	151.8 ± 5.8	151.2 ± 6.4	150.7 ± 5.5	148.2 ± 7.3*
Ankle joint angle at TD	101.1 ± 4.6	100.5 ± 6.4	101.5 ± 3.7	100.6 ± 5.6
Minimum knee joint angle	138.4 ± 6.2	136.9 ± 8.6	134.9 ± 7.1*	138.2 ± 7.1
Minimum ankle joint angle	79.1 ± 4.5	79.3 ± 5.0	78.1 ± 4.2*	78.7 ± 4.3
Hip joint extension-flexion angle at TO	200.7 ± 5.4	200.8 ± 5.7	198.9 ± 4.8	201.2 ± 5.3
Knee joint angle at TO	161.1 ± 5.9	159.5 ± 7.7	157.6 ± 4.8	164.4 ± 4.8*
Ankle joint angle at TO	128.4 ± 8.4	126.9 ± 7.3	126.6 ± 8.8	126.3 ± 6.9
Joint angular velocity [deg/s]				
Maximum hip joint extension angular velocity	918.5 ± 87.2	912.8 ± 92.7	906.6 ± 83.2	924.8 ± 92.7
Maximum knee joint extension angular velocity	577.2 ± 138.9	570.4 ± 149.7	579.7 ± 137.4	585.2 ± 124.3
Maximum ankle joint plantar flexion angular velocity	1258.3 ± 163.6	1233.8 ± 148.8	1210.5 ± 172.7	1254.4 ± 119.4

*Note. Values are expressed as mean ± standard deviation. * Significant difference between straight and curved paths on each side. TD: Touch down, TO: Take-off.*

Table 2 shows the differences in the ground reaction force parameters in inside and outside the leg on straight and curved paths. The minimum (inside: p < .01, d = 1.32; outside: p < .01, d = 1.39) and maximum (inside: p < .01, d = 1.77; outside: p < .01, d = 1.56) medial-lateral GRF and the impulse (inside: p < .01, d = 1.61; outside: p < .01, d = 1.56) for both legs on the curved path were significantly greater than on the straight path. Additionally, the maximum posterior GRF (p < .01, d = 0.87) and impulse (p < .01, d = 0.81) for the outer leg on the curved path were significantly lower than those on the straight path, but there was no significant difference for the inside leg. However, there were no significant differences in the vertical component between groups or paths.

Table 2. Differences in Ground reaction forces parameters in inside and outside the legs on straight and curved paths.

	Straight		**Curve**	
	Inside	Outside	Inside	Outside
Minimum medial-lateral GRF [N]	-533.7 ± 133.6	-352.8 ± 211.3	-289.9 ± 224.2*	-104.3 ± 138.5*
Maximum medial-lateral GRF [N]	355.4 ± 186.1	496.5 ± 175.7	818.4 ± 320.1*	780.5 ± 188.6*
Medial-lateral impulse [Ns]	3.5 ± 13.2	-1.8 ± 12.0	33.1 ± 22.4*	26.4 ± 22.6*
Minimum anterior - posterior GRF [N]	-1624.5 ± 278.1	-1518.7 ± 364.8	-1566.2 ± 144.8	-1423.2 ± 255.8
Anterior impulse [Ns]	-30.6 ± 4.3	-30.9 ± 6.4	-30.0 ± 6.7	-29.5 ± 4.0
Maximum anterior - posterior GRF [N]	1164.3 ± 121.3	1184.4 ± 103.8	1142.4 ± 123.2	1093.8 ± 104.7*
Posterior impulse [Ns]	38.3 ± 5.4	37.0 ± 3.2	39.4 ± 5.3	33.8 ± 4.6*
Vertical peak GRF [N]	2592.3 ± 382.7	2772.1 ± 503.0	2474.9 ± 317.6	2589.8 ± 412.2
Vertical impulse [Ns]	150.8 ± 16.4	152.5 ± 18.5	152.3 ± 21.8	150.3 ± 15.6
Maximum total GRF [N]	2647.5 ± 361.4	2853.1 ± 520.8	2547.9 ± 411.0	2661.0 ± 394.5

*Note. Values are expressed as mean ± standard deviation. * Significant difference between straight and curved paths on each side.*

DISCUSSION

To enable curved running, it is necessary to produce a centripetal force with respect to the centre of curvature. The minimum and maximum medial-lateral GRF and impulse for both legs on the curved path were significantly greater than those on the straight path. These results indicate that the centripetal force is produced in the direction of the centre of curvature in the curved path. In addition, previous studies indicated that the running speeds in curved paths were slower than those in straight paths (Chang and Kram, 2007; Churchill et al., 2015; Churchill et al., 2016; Stoner and Ben-sira, 1979). The results of this study support those of many previous studies. Therefore, these results were reasonable in terms of the kinematics and kinetic characteristics during running on a curved path.

The ARV for the MG in the inside leg on the curved path was greater than that on the straight path, and there was no significant difference between the straight and curved paths in the maximum total GRF in this study. On the other hand, in the previous study which investigated EMG during running in curved path with a small radius of curvature (Smith et al.,1997), it was reported that there was no significant difference between straight and curved paths in EMG, and the maximum total GRF for the inside leg in curved path was smaller than that in straight path (Chang and Kram,2007; Smith et al.,2006). Therefore, in the inside leg, it is considered that the muscle activity for MG was involved in producing GRF equivalent to a straight path to enable sprinting in a curved path with a radius of curvature. Additionally, the minimum knee and ankle joint angles for the inside leg on the curved path were significantly smaller than those on the straight path. The results showed that the ankle joint angle for the inside leg was dorsiflexed in the curved path. Dorsiflexion of the ankle joint may cause a change in the muscle tendon complex length, and it is possible to perform concentric contraction at a high level by enhancing the activity level of eccentric contraction in the MG; consequently, it has been involved in producing greater force.

On the other hand, in the outer leg, it was inferred that the decrease in the anterior-posterior GRF and impulse for the outside leg could be caused by a decrease in running speed on a curved path, but there were no significant differences in the electromyogram between the paths for any muscle. In a study on electromyograms during sprinting, previous studies have reported that activity in the soleus muscle increases with running speed during the stance phase (Kuitunen et al., 2002), and that the semimembranosus and semitendinoid muscles were activated in the latter half of the stance phase (Schache et al.,2012). In addition, Tottori et al. (2016) investigated the relationship between running time on the curved path and cross-sectional area of the psoas major muscle using magnetic resonance imaging and showed that runners in whom the cross-sectional area of the psoas major muscle of the outer leg was larger than that of the inner leg were faster in curve sprinting. Therefore, it is considered that the activities of muscles that were not analysed in this study had an influence on the reduction of the ground reaction force for the outside leg and a decrease in running speed on the curved path. Otherwise, for the activities of muscles that were analysed in this study, it would have been an influence that these were not recruited more than in the straight path.

The muscles targeted in this study were limited to six points for each leg. Furthermore, these are the only points that can be derived from the surface. To investigate the muscle activities in curved sprinting in detail, it will be possible to evaluate the mobilization of muscle activity by analysing the T2 signals using MRI. In addition to examining only the amplitude of activity using ARV, an approach based on muscle synergies is also an issue that should be investigated in the future.

CONCLUSION

It was clarified that there were differences in the characteristics of surface electromyogram inside and outside the leg during curved sprinting between straight and curved paths, and ARV for MG in the inside leg on a curved path was greater than that on a straight path, but not in the outside leg. These results suggest that electromyographic strategies for performing curved sprinting with a large radius of curvature differ between the inside and outside legs.

AUTHOR CONTRIBUTIONS

Conceptualization: H.O. and A.K.; methodology: H.O.; software: H.O.; validation: H.O., Y.C. and T.Y.; formal analysis: H.O.; investigation: H.O. and T.Y.; resources: H.O. and Y.C.; data curation: H.O., Y.C. and T.Y.; writing—original draft preparation: H.O.; writing—review & editing: H.O., A.K., Y.C. and T.Y.; visualization: H.O.; supervision: H.O. and T.Y.; project administration: H.O. and Y.C.; funding acquisition: H.O. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Activation of upper- and lower-limb muscles during hook punch using lead- and rear-arm

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ABSTRACT

The hook punch is a fundamental technique in boxing, requiring coordinated activation of upper- and lower-limb muscles to generate maximal force and speed. While previous studies have analysed muscle activation in straight punches, research on hook punches remains limited. This study aimed to examine the peak activation (PA) and average rectified value (ARV) of seven upper- and lower-body muscles during four distinct hook punch techniques and compare activation patterns between Southpaw (SP) and Orthodox (OD) stance boxers. Twelve elite male boxers (SP: n = 8, OD: n = 4) participated in this study. Surface electromyography recorded PA and ARV of the biceps brachii (BB), triceps brachii (TB), anterior deltoid (AD), latissimus dorsi (LD), biceps femoris (BF), rectus femoris (RF), and medial gastrocnemius (MG) during four hook punch techniques: lead-arm hook to the head (LAHH), lead-arm hook to the body (LAHB), rear-arm hook to the head (RAHH), and rear-arm hook to the body (RAHB). The independent t-test and Wilcoxon test compared stance groups, while the paired t-test was used to determine intra-technique differences. No significant differences in PA or ARV were found between SP and OD, except for RF activation during LAHB (p = .038). Significant intra-technique differences were observed in LD, RF, and MG activation. In conclusion, no differences in muscle activation were observed between SP and OD stances, except for the rectus femoris during the LABH. Between punch techniques, variation in muscle activation was observed, implying differences in strategies used.
Keywords: Biomechanics, Athletic performance, Muscle strength, Combat sports, Musculoskeletal physiological phenomena, Muscle contraction.

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INTRODUCTION

Several combat sports are practised worldwide by athletes, either as a part of cultural traditions or as a competitive event (e.g., boxing, wrestling, judo, etc.). Boxing is unique among these combat sports because it allows punches, unlike other combat sports that involve techniques such as holding, kicking, grappling, elbow and knee strikes (Lenetsky et al., 2020). In the sport of boxing, precise, quick, and powerful punches enhance the likelihood of success (Beattie & Ruddock, 2022; Cheraghi et al., 2014). Different types of punches can be actually used during a competitive match. Within several types of punches in boxing, the hook is one of the most common and effective punches due to its ability to generate significant force with high speed from close range (Dinu et al., 2020; Smith et al., 2000; Thomson & Lamb, 2016). The hook technique can be used in different situations, such as in combination with other offensive punches or as a counterpunch while blocking. It can also be used to get an advantage over the opponent, to knock the opponent out, or to score a point (Lenetsky et al., 2013). Indeed, the chances of the opponent getting knocked out are higher if the hook strikes the opponent's chin (Walilko et al., 2005). However, it should also be noted that performing a hook punch may also be risky. For example, if the athlete misses the opponent during the hook punch, the opponents may then have an ample opportunity to counterpunch (Bingul et al., 2018).

Furthermore, the hook punch can be thrown from two different stance positions (i.e., southpaw and orthodox). The "*southpaw stance*" in boxing is characterized by the right foot and hand being positioned in front, while the left foot and hand are positioned behind, which is a natural setup for left-handed fighters. In contrast, the "*orthodox stance*" is the opposite configuration, with the left foot and hand leading, a position commonly adopted by right-handed individuals (Buśko et al., 2014). Moreover, the hook punch technique varies based on the arm used to deliver the punch (i.e., the lead arm hook, thrown with the front hand; the rear arm hook, thrown with the backhand) and the target area where the punch is thrown (i.e., the body hook, targeting the opponent's ribs or liver area; and the head hook, which targets the chin, jaw, temple or side of the head) (Bingul et al., 2018; Kapo et al., 2021). Research indicates that the execution of hook punches involves significant rotational movements, particularly from the trunk and lower limbs. For instance, Dunn et al. (2022) emphasize that the trajectory of the arm during hook punches is characterized by an arcing motion, which necessitates a high degree of rotational acceleration delivered to the target (Dunn et al., 2022). This rotational component is crucial for generating the force required to deliver an effective punch. Furthermore, the contribution of lower limb musculature is vital, as it provides the necessary stability and power transfer through the kinetic chain during the punch (Dunn et al., 2022; Zhou et al., 2022).

Of note, the upper and lower-body muscular strength is essential in boxing for generating high force and sustaining a higher level of competitiveness (Bingul et al., 2018). Therefore, understanding the muscle activation patterns during these hook punches is crucial for identifying the primary muscle groups involved, assessing the load and potential injury risks, developing new training programs to enhance the punching efficiency, and refining the hook techniques – all leading to better performance (Oliva-Lozano & Muyor, 2020; Raizada & Bagchi, 2019; Türker & Sze, 2013). Assessing the muscle activation during specific movement is possible with the use of surface electromyography (sEMG), which is a non-invasive technique for recording the electrical activity of targeted muscles (Bagchi & Raizada, 2019; Massó et al., 2010; Raizada & Bagchi, 2017).

Previous studies have used sEMG to record muscle activation in boxing for different punches. For example, Valentino et al. (1990) conducted an electromyographical study in boxing, comparing muscle activation during the jab technique with the uppercut. The authors reported that deltoid muscle activation was significantly higher during the jab than the uppercut. Similarly, Kumar et al. (2022) analysed the peak activation during different jab techniques, finding significantly higher peak activation of the anterior deltoid during long-range targeting head as compared to other jab techniques. Moreover, a few studies (Izumi et al., 2009; Kumar et al., 2022; Lockwood & Tant, 1997) have analysed the upper and/or lower body muscle activation patterns during different punching techniques. Despite the significance of hook punches in boxing, no previous study has investigated muscle activation during hook punches. Although one study did measure the force of impact during different hook punches, the authors did not assess muscle activation (Bingul et al., 2018). Therefore, the current study aimed to investigate the peak activation (PA) and average rectified value (ARV) of seven upper and lower body muscles during four distinct hook techniques (i.e., lead arm hook to the head, lead arm hook to the body, rear arm hook to the head, and rear arm hook to the body). Specifically, the first objective was to compare the PA and ARV of seven upper and lower body muscles between Southpaw and Orthodox stance boxers during the execution of four distinct hook techniques. The second objective was to compare the PA and ARV values among four hook techniques for each muscle separately.

METHODOLOGY

Participants

The sample size was determined using the G*Power software version 3.1.9.7 (University of Dusseldorf, Dusseldorf, Germany). A priori analysis indicated that a minimum of 5 samples was necessary, based on the following variables: effect size = 0.80 (large), α error probability = .05, power = 0.95, number of groups = 1, and number of measurements = 4 (referring to four different hook techniques). Additionally, the correlation among repeated measures was set at .05, with a non-sphericity correction of € = 1. A purposive-convenience sampling technique was used for the recruitment of participants. The inclusion criteria were as (i) elite boxing player (i.e. participated in international competition such as world championship, Asian championship, Commonwealth Games, etc.), (ii) had a minimum of 6 years training experience, (iii) free from injury during the past 6 months. Therefore, a total of 12 male elite boxers (southpaw stance, n = 8 and orthodox stance, n = 4), slightly higher than the recommended sample size, were selected for the study considering the potential participants' attritions due to difficulties related to EMG recordings (Turker & Sözen, 2013). However, we encountered no difficulties in capturing the EMG data of any participant. The descriptive characteristics of participants are presented in Table 1. The study was conducted in accordance with the ethical guidelines outlined in the Declaration of Helsinki. Each participant received comprehensive information regarding the potential risks and benefits of their involvement, and written informed consent was obtained prior to enrolment in the study. This study was conducted as part of a doctoral program and received approval from the Departmental Research Committee (DRC) at the Department of Sports Biomechanics, Lakshmibai National Institute of Physical Education, Gwalior, India.

Table 1. Anthropometric and demographic characteristics of participants.

Variables	Overall (n = 12)	Southpaw (n = 8)	Orthodox (n = 4)
Age (yrs)	24.4 ± 2.7	24.0 ± 3.0	25.3 ± 1.8
Height (cm)	167.9 ± 4.2	167 ± 4.5	169.8 ± 3.3
Body mass (kg)	58.7 ± 4.7	57.7 ± 5.2	60.7 ± 3.1
BMI	20.8 ± 1.3	20.7 ± 1.3	21.1 ± 1.4

Note. Data are presented as mean ± standard deviation, BMI – body mass index.

Experimental design

The EMG activity of seven muscles—biceps brachii (BB), triceps brachii (TB), anterior deltoid (AD), latissimus dorsi (LD), biceps femoris (BF), rectus femoris (RF) and medial gastrocnemius (MG)—was recorded during the execution of four hook punch types: (i) leading arm hook to the head; (ii) leading arm hook to the body;

(iii) rear arm hook to the head; and (iv) rear arm hook to the body. The experimental design involved repeated measures, with participants performing each punch type three times with a 1-minute rest interval between trials in a randomized crossover manner (www.randomizer.org).

Equipment and measurements

The EMG activity of the muscles was recorded using a portable wireless surface EMG device (BTS FREEEMG, Bioengineering, Italy), which comprises of probes, a USB receiver, and specialized EMG-Analyzer software. The device's signals from selected seven muscles were recorded at a 1000 Hz sampling rate, transmitted via a USB receiver, and processed using the accompanying software, with all values expressed in microvolts (µV) for all four-hook punch types. To ensure consistency in performance, participants used standard training gloves that adhered to size and weight specifications outlined by the International Boxing Association (AIBA, 2010). Additionally, a medium-sized punching bag (36” × 18”) was hung in the practice area, providing a standardized target for all punch techniques.

Data collection

Before the data collection, familiarization sessions were conducted for all participants, where they were briefly instructed about the study protocol and were given ample time to adapt to the test procedure. They were instructed to remove their upper-body clothing to facilitate proper placement of the EMG probes. The target muscles were located using manual palpation as described in a previous study (Kothari et al., 2014). The placement of the EMG probes followed the guidelines provided by the SENIAM project (Hermens et al., 1999). To minimize skin impedance, the designated areas were shaved and cleaned with alcohol swabs (Non-Woven Alcohol Swab, Recombigen Clear & Sure, India).

Surface EMG electrodes (H124SG, Adafruit, USA) were carefully positioned along the muscle fibre lines and securely attached to wireless EMG probes using adhesive medical tape (Mendwell Adhesive Tape USP, Prominence Healthcare Pvt. Ltd., India) to ensure they remained fixed during punching. The wireless probes transmitted data to a USB receiver connected to a laptop, and the data was processed using EMG-Analyzer software. The BTS FREEEMG system was calibrated as per the manufacturer's instructions *("Bts freeemg 300 user manual*," 2013). Normalization of the recorded EMG signal was not conducted in this study, as it aimed to compare the amplitude signals between the same muscles during different punches within the same session and under consistent experimental conditions. Additionally, there were no alterations to the EMG electrode setup throughout the process (Halaki & Ginn, 2012).

After electrode placement, participants completed a 2-minute warm-up, including shadow boxing with a focus on the hook techniques. The adhesive quality of the EMG electrodes and probes was rechecked post-warm-up. Each participant was then instructed to execute the techniques individually. Participants were encouraged to execute each punch with maximum effort; however, no external motivation was given. The punching bag was marked with temporary rectangles corresponding to the participant’s height: "*head length* × *head width*" at head level for head-targeting punches and "*torso length* × *shoulder width*" at body level for body-targeting punches. Participants were instructed to throw the hook to the head and body from a stationary position using the leading arm, while for the rear arm; they were required to take a step forward. The average of three trials was calculated for each punch type and muscle group in Microsoft Office Excel (Microsoft Office Professional Plus 2019).

Statistical analysis

Descriptive statistics were employed to summarize the dataset, utilizing mean and standard deviation values for normally distributed variables, whereas median and interquartile range (IQR) values for variables not conforming to normal distribution. The normality assumption of the collected data was assessed using the Shapiro-Wilk test. To analyse muscle activations in different techniques between SP and OD Stances, an independent sample T-test was employed for variables exhibiting a normal distribution, while the Mann-Whitney U test was utilized for variables following non-normal distributions. The muscle activation during the four techniques was compared using a series of paired sample T-tests for variables exhibiting a normal distribution and Wilcoxon tests for those variables demonstrating a non-normal distribution. Additionally, the effect size (ES) for the Wilcoxon test was computed using the formula 'r' = Z/√n (Tomczak & Tomczak, 2014), where the magnitude of 'r' was interpreted as small (≤0.1), moderate (>0.3–0.5), and large (>0.5) (Cohen, 1988). Hedge's *g ES was calculated* for the paired sample T-test, which was categorized as trivial (<0.2), small (0.2–0.6), moderate (>0.6–1.2), or large (>1.2–2.0) (Hopkins et al., 2009). Figures were generated using GraphPad Prism version 8.0. Statistical analyses were conducted using IBM SPSS version 24.0, with a predefined significance level set at $p \leq .05$.

RESULTS

The comparative statistics of EMG activity (PA and ARV) for the selected muscles during the four hook punch techniques (LAHH, LAHB, RAHH, RAHB) between Southpaw and Orthodox stances are summarised in Table 2. No significant differences ($p > .05$) were observed in PA and ARV of all selected muscles between SP and OD stance boxers during the four-punch technique. The only exception was the PA in the RF muscle during the LAHB punch technique, which showed a significant difference ($p = .038$; r = 0.627). Additionally, a non-significant but large effect size (r = 0.513; r = 1.886) was noted in the PA of the BF muscle between the two stance groups during the LAHH and LAHB punch techniques, respectively.

The graphical representation in Figure 1 highlights the variations in muscle activation for PA and ARV across the four hook punch techniques. For overall PA (Figure 1a), significant differences were noted in the LD between LAHH and RAHH ($p = .02$, Large ES = 0.804), in the RF between LAHH and LAHB ($p = .019$, Large ES = 0.812) and in the MG between LAHH and RAHH ($p = .033$, Large ES = 0.64) as well as between LAHB and RAHB ($p = .016$, Large ES = 0.72). In the Southpaw PA (Figure 1b), a significant difference was detected in the Biceps Brachii muscle between LAHB and RAHB ($p = .047$, Large ES = 0.880). Similarly, in the Orthodox PA (Figure 1c), a significant difference was found in the Biceps Brachii muscle between LAHH and LAHB ($p = .045$, Large ES = 1.443). For overall ARV (Figure 1d), significant differences were observed in the Biceps Brachii between RAHH and RAHB ($p = .015$, Large ES = 0.802) and in the Biceps Femoris between LAHH and LAHB ($p = .030$, Medium ES = 0.734) and between RAHH and RAHB ($p = .028$, Large ES = 0.63). In the Southpaw ARV (Figure 1e), the BB muscle displayed significant differences in ARV between RAHH and RAHB ($p = .017$, ES = 0.84). However, no significant differences in ARV were observed in the Orthodox stance (Figure 1f).

DISCUSSION

The first objective of the current study was to compare the PA and ARV of seven upper- and lower-body muscles during four hook punch techniques between SP and OD stances. The primary findings revealed non-significant differences in PA and ARV of selected muscles between stance groups, except for the PA in RF during the LAHB technique. The lack of significant differences in muscle activation between SP and OD stances aligns with the hypothesis that elite athletes, regardless of stance, may exhibit similar neuromuscular activation to optimize force generation during hook punches. For instance, Bingul et al. (2018) observed no significant differences in impact force or joint kinetics during hook punch throws between SP and OD stance elite boxers.

Table 2. Comparative statistical analysis of muscle activations in different techniques for southpaw and orthodox stances.

	Southpaw (n = 7)	Orthodox (n = 4)	*p*-value [g/r]	Southpaw (n = 8)	Orthodox (n = 4)	*p*-value [g/r]
	Mean ± SD	**Mean ± SD**	**Magnitude**	**Mean ± SD**	**Mean ± SD**	**Magnitude**
	Lead arm hook (head)			**Rear arm hook (head)**		
Biceps Brachii (Peak activation)	1908.3 ± 223.7	1759.9 ± 164	.28 [0.659][s]	1947 ± 296.2	1840.9 ± 295.1	.571 [0.331][s]
Triceps Brachii (Peak activation)	954.5 ± 363.1	923.6 ± 172	.878 [0.09][t]	1049.8 ± 259.6	869.5 ± 174.2	.243 [0.701][m]
Anterior Deltoid (Peak activation)	1348.8 ± 459.2	1336.4 ± 156.7	.96 [0.029][t]	1239.3 ± 339.8	1047.5 ± 246.2	.343 [0.562][s]
Latissimus Dorsi (Peak activation)	607.4 ± 202.2	758.8 ± 154.6	.23 [0.737][m]	490.3 ± 185.7	508.9 (96)[a]	.865[b] [0.051][s]
Biceps femoris (Peak activation)	502.1 (44.6)[a]	621.7 ± 87.2	.089[b] [0.513][l]	514.2 (459)[a]	547.4 ± 131.7	.734[b] [0.102][s]
Rectus femoris (Peak activation)	617.6 ± 143.4	733.8 ± 291.9	.39 [0.517][s]	635.2 ± 268	524 ± 113.6	.453 [0.441][s]
Medial gastrocnemius (Peak activation)	610.3 (371)[a]	588.4 (460.3)[a]	.45[b] [0.228][s]	1018.7 ± 400.9	918.3 (643)[a]	.497[b] [0.205][s]
Biceps Brachii (average rectified value)	96 ± 20.9	99.1 ± 17	.81 [0.142][t]	103 (37.2)[a]	116.5 ± 30.3	.734[b] [0.102][s]
Triceps Brachii (average rectified value)	36 ± 15.5	43.5 ± 8.2	.401 [0.505][s]	28.5 ± 10.2	31.6 ± 8.8	.622 [0.288][s]
Anterior Deltoid (average rectified value)	52.1 ± 15	42.8 (31.4)[a]	.257[b] [0.342][m]	56.2 (12.7)[a]	59.7 ± 7.3	.234[b] [0.358][m]
Latissimus Dorsi (average rectified value)	28.5 (14.4)[a]	37.5 ± 6.2	.131[b] [0.456][m]	24.1 (11)[a]	30.8 ± 1.7	.174[b] [0.410][m]
Biceps femoris (average rectified value)	35.9 ± 10.6	40.8 ± 4	.406 [0.5][s]	40.5 (35.2)[a]	66.9 (23)[a]	.126[b] [0.461][m]
Rectus femoris (average rectified value)	46.7 ± 12.3	65 ± 37.2	.403 [0.706][m]	41.6 ± 13.4	43 ± 4	.849 [0.11][t]
Medial gastrocnemius (average rectified value)	57.8 ± 19.1	38.8 ± 17	.136 [0.938][m]	65.7 ± 17	61.4 (24.8)[a]	.61[b] [0.154][s]
	Lead arm hook (body)			**Rear arm hook (body)**		
Biceps Brachii (Peak activation)	1939.4 ± 224	1900.5 ± 184.4	.776 [0.168][t]	1714 ± 429.8	1978.4 ± 199.5	.277 [0.649][m]
Triceps Brachii (Peak activation)	987.6 ± 394.2	1179.5 ± 149.8	.382 [0.526][s]	995.6 ± 288.2	1003.7 (64.2)[a]	.174[b] [0.410][m]
Anterior Deltoid (Peak activation)	1315.7 ± 360.2	1138.8 ± 234.8	.406 [0.499][s]	1189.1 ± 320.7	1259.1 ± 63.6	.681 [0.239][s]
Latissimus Dorsi (Peak activation)	611 ± 174.1	711 ± 78.5	.313 [0.612][m]	467.3 (387.5)[a]	685.7 ± 81.7	.174[b] [0.410][m]
Biceps femoris (Peak activation)	493.8 ± 110.7	1012.2 ± 406	.081 [1.886][l]	582.6 (333.4)[a]	586.7 ± 188.3	.734[b] [0.102][s]
Rectus femoris (Peak activation)	531.1 (153.4)[a]	575 (332.3)[a]	.038[*b] [0.627][l]	604.4 ± 186.3	462.9 ± 109.7	.197 [0.781][m]
Medial gastrocnemius (Peak activation)	642.3 ± 189.7	420.2 ± 270.9	.142 [0.922][m]	664.1 (661.5)[a]	543.2 ± 357.5	.308[b] [0.307][m]
Biceps Brachii (average rectified value)	95.8 ± 21.9	115.6 ± 33	.258 [0.691][m]	100.1 ± 30.7	112.6 ± 32.4	.529 [0.369][s]
Triceps Brachii (average rectified value)	34.1 ± 14.4	45.8 ± 14.1	.226 [0.745][m]	28.2 (21)[a]	37.1 ± 5.9	.396[b] [0.256][s]
Anterior Deltoid (average rectified value)	51 ± 8.3	51.7 ± 13.8	.913 [0.064][t]	53.6 ± 11.3	59.8 ± 7.8	.354 [0.55][s]
Latissimus Dorsi (average rectified value)	29.6 ± 9.5	37.1 ± 5.4	.188 [0.817][m]	25.4 (17.3)[a]	31.3 ± 1.4	.174[b] [0.410][m]
Biceps femoris (average rectified value)	40.3 ± 10.1	53.2 ± 15.9	.129 [0.956][m]	53.9 (58.6)[a]	72.2 ± 11.9	.308[b] [0.307][m]
Rectus femoris (average rectified value)	46 ± 9.7	69.1 ± 40.8	.343 [0.847][m]	46.1 ± 20.1	43.4 ± 2.3	.802 [0.146][t]
Medial gastrocnemius (average rectified value)	58.2 ± 13.3	48.3 ± 23.7	.388 [0.519][s]	69.8 ± 26.8	52.9 ± 14.2	.272 [0.657][m]

Note: [*] - Significant at .05 level; [a] – Median (Inter Quartile Range);[b] – Mann Whitney U Test; g – Hedge's g Correction; r – Correlation Coefficient; [t] – Trivial Effect Size; [s] – Small Effect Size; [m] – Medium Effect Size; [l] – Large Effect Size.

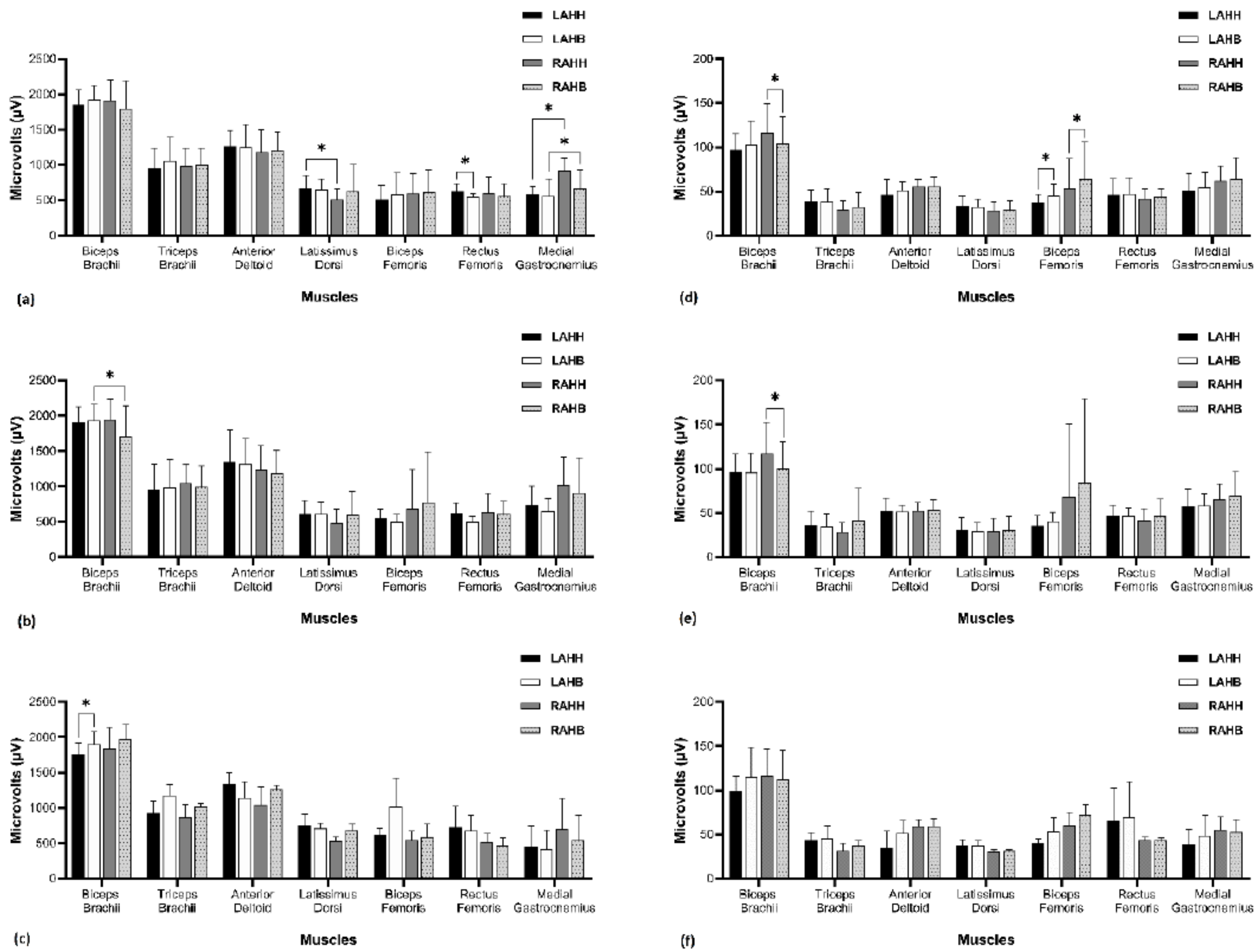

Figure 1. Comparison between lead arm hook to head (LAHH), lead arm hook to body (LAHB), rear arm hook to head (RAHH), and rear arm hook to body (RAHB) for biceps brachii, triceps brachii, anterior deltoid, latissimus dorsi, biceps femoris, rectus femoris, and medial gastrocnemius. (a) Overall peak activation, (b) Southpaw peak activation, (c) Orthodox peak activation, (d) Overall average rectified value, (e) Southpaw average rectified value and (f) Orthodox average rectified value, *$p < .05$.

Furthermore, the possible reason for the only difference observed in PA of RF during LAHB could be that OD boxers typically position their dominant (rear) leg farther back, potentially increasing reliance on the RF for stabilizing the lead leg during body-targeted hooks. Conversely, SP may distribute force more evenly, reducing the demand from RF muscles, as previous research found a significant difference in stride lengths during hook punch between SP (66.97 ± 15.34 cm) and OD (84.74 ± 7.88 cm) boxers (Bingul et al., 2018). Moreover, it aligns with Turner et al. (2011), who reported that stance orientation significantly influences lower limb muscle activation during rotational movements in combat sports.

However, Bingual et al. (2017) also reported that the OD stance generates higher impact force and acceleration compared to the SP stance in the straight punch technique. Nonetheless, straight punches travel directly forward by extending the elbow, whereas hook punches curve around and upwards, relying on shoulder flexion and adduction, which allows for a wider range of motion in a hook punch compared to a jab or cross. Additionally, the path of acceleration for a hook punch can be longer than that of a straight punch (Piorkowski et al., 2011). Of note, the significant differences in kinetics and kinematics between SP and OD stances during straight punches do not provide evidence of a difference in muscle activation between SP and OD stances. However, in a previous study, Dyson et al. (2007) reported higher muscle activity when the impact forces were high. Our study is the first of its kind, which directly compared the muscle activation pattern between the two stances during varied hook punch techniques in boxing, and the findings can be used as a proof-of-concept for future studies.

The secondary objective of the study was to compare each muscle's PA and ARV among four kinds of hook techniques. We found divergent results in PA and ARV in BB muscle in OD and SP stance boxers. While there was no significant difference in PA of BB, a significant difference was observed in ARV of BB between RAHH and RAHB techniques. This underscores the importance of selecting both EMG data-reduction methods, where PA captures transient, high-intensity bursts (e.g., explosive punch initiation), and ARV reflects sustained muscle activity over the movement cycle (Hibbs et al., 2011). Of note, lead arm hook punches are often performed with more velocity (closest to the target), whereas rear arm hook punches primarily rely on more force (furthest from the target) (Dyson et al., 2007). Further, the increased scapular retraction and trunk rotation in the lead-arm hook to generate a higher velocity punch might amplify the LD engagement to stabilize the torso, which explains the significant difference observed in PA of LD between LAHH and RAHH.

As previously Dyson et al. (2007) reported higher punching velocity and force when the target area was head over the body. Similarly, this study validated higher PA in RF during LAHH compared to LAHB. Furthermore, Dyson et al. (2007) mentioned that MG was the first muscle to be recruited when punches were delivered with maximal force to the head. This justifies the higher MG activation during RAHH, reflecting increased plantar flexion demands to drive rotational power from the lower body. In both lead and rear arm hooks, the BF exhibited higher ARV when it was thrown to the body compared to the head. Hooks aimed at the body require a downward trajectory and often involve trunk and knee flexion or forward lean to reach the opponent's midsection, which might increase the demand on BF muscles (Quinzi et al., 2015). The observed activation patterns highlight key training applications: Coaches should strengthen the BF for body hooks due to their prominence in LAHB and RAHB, while targeting the LD and MG can enhance force generation and stability during head hooks. Additionally, eccentric BB strength training can reduce injury risk during deceleration phases, given its dominance in hook punches. Training programs need not be stance-specific for elite athletes, though individualized adjustments, such as optimizing RF engagement in Southpaws, may further enhance performance. Besides the aforementioned practical applications, a few limitations should be acknowledged. Although a priori sample size estimation was performed the unequal group sizes (Southpaw:

n = 8 vs. Orthodox: n = 4) may limit statistical power and generalizability. Additionally, the activation pattern might differ in competition (i.e. in the ring) and in simulated combination punches (i.e. in the lab) (Pierce et al., 2007). Furthermore, we skipped normalizing EMG data to task-specific maximal voluntary contractions as proposed in dynamic normalization protocols, which could allow inter-muscle comparability (Halaki & Ginn, 2012).

CONCLUSION

This study revealed no significant differences in muscle activation between SP and OD stances, except for the rectus femoris during the lead-arm body hook. Significant variations were observed in the latissimus dorsi, rectus femoris, and medial gastrocnemius, emphasizing the necessity for muscle-specific conditioning to potentially optimize performance. These findings contribute to a deeper understanding of neuromuscular demands in boxing and provide valuable insights for training strategies tailored to enhance hook punch execution.

AUTHOR CONTRIBUTIONS

Study design: SC and RKT; data collection: SC and PP; data curation: SC and PP; data analysis: AB and RKT; writing: SC, PP, TM, PS, TSB, AB, and RKT. All authors have approved the publication of the final version of the manuscript.

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ORIGINAL ARTICLE

Somatotype and body composition based on playing position in Peruvian U-20 football players

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ABSTRACT

Background. Football, like other sports, necessitates the development of specific skills to achieve optimal performance. Furthermore, the roles of each player must be individually tailored, taking into account their physical composition and body structure. This underscores the importance of understanding the anthropometric and morpho structural characteristics of athletes. In this context, the aim of the present study was to describe these characteristics in a sample of U-20 youth soccer players, based on their playing positions on the field. Methods. This study employed a cross-sectional design. A non-probabilistic sample of 120 athletes, aged 17 to 20, was drawn from a professional soccer club in Lima, Peru. Twenty-three anthropometric variables were measured following the protocols of the International Society for the Advancement of Kineanthropometry (ISAK), using Kerr's 5-component method for body composition and the Carter and Heath somatotype classification. Results. The Kerr anthropometric method demonstrated high accuracy in estimating body weight (R^2 = .956, p < .05), with good agreement as confirmed by the Bland-Altman analysis. Significant differences were observed in favour of goalkeepers in variables such as height, weight, skinfold thickness, thigh and calf circumferences, biacromial diameter, humerus and femur breadths, as well as arm and forearm circumferences, compared to defenders, midfielders, and forwards. However, defenders demonstrated significantly greater thorax and calf perimeters (p < .05). Significant differences were also observed in body composition indicators, as per Kerr's method, including adipose tissue, muscle mass, bone mass, and skinfold thickness, with goalkeepers showing higher values (p < .05). All groups were classified as balanced mesomorphs. Conclusion. The results emphasize the importance of tailoring training and nutritional interventions to the specific morpho structural characteristics of soccer players, based on their playing position.
Keywords: Sport medicine, Cineanthropometry, Soccer, Youth, Body composition, Somatotypes.

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INTRODUCTION

Football is one of the most popular sports worldwide and the most widely practiced in our country, whether at the professional, recreational, or amateur level. At the professional level, the practice of football requires the development of specific capacities such as reaction speed, movement speed, leg power, cardiorespiratory endurance, muscular endurance, muscular power, lower body strength, upper body muscular strength, agility, coordination, and appropriate body composition (Ramírez Marrero & Rivera, 1992). Football, like many other sports, requires the development of specific characteristics to achieve optimal performance on the field (Rampinini et al., 2009). Similarly, the roles of each athlete must be individualized according to their body shape and structure (Rienzi et al., 2000).

In modern sports, optimizing performance requires selecting athletes based on their morpho structure, such as height, which allows for greater reach; muscle mass, which is associated with strength and power; and reduced fat mass, which facilitates lower body weight, thereby increasing running speed and reducing energy expenditure (Jorquera et al., 2013). Moreover, a distinctive feature of team sports is the variation in physical demands across playing positions, which may result in physiological differences among athletes based on their position on the field (Bangsbo, 2016).

The player's morphological characteristics can be a determining factor in the team's tactical approach. When selecting an athlete, it is essential to consider the extent to which specific morphological traits are required for a particular playing position (Casajús, 2001; Gil et al., 2007; Hazir, 2010). In this regard, there appears to be a consensus that the body shape of professional football players typically corresponds to a balanced mesomorph somatotype. However, the differences according to playing position remain less well-defined (Henríquez-Olguín et al., 2013).

In a study conducted on Portuguese youth football players, the authors concluded that physical training has a direct impact on the development of the athletes' aerobic capacity. However, other untrained physical characteristics, such as height and body weight, were factors that positively influenced performance in the vertical jump and the 30-meter sprint test (Malina et al., 2004). On the other hand, youth athletes selected for competition based solely on their technical skills, without considering their physical structure, are more likely to face professional failure due to inadequate height, suboptimal muscle mass, or an increased risk of chronic injury from insufficient physical strength (Arnason et al., 2004).

These morphological and structural parameters are essential for both the evaluation and selection of athletes (Jorquera et al., 2013). There are currently no national reference standards for these parameters, which would be highly valuable for the physical optimization of youth football players, serve as a reference for athlete selection during the developmental stage, and contribute to future research in sports science. Currently, there is a lack of comprehensive information regarding the morphological and structural characteristics of Peruvian youth football players. Therefore, the objective of the present study is to describe and compare the morphological and anthropometric characteristics of Peruvian U-20 youth football players and examine their relationship with playing position on the field.

METHODS

Design, type of research, and participants

The present study utilized a cross-sectional design. The subjects were selected through a non-probabilistic convenience sampling method, consisting of 120 athletes aged 17 to 20, all belonging to a professional football club. The inclusion criteria considered an age range of 17 to 20 years, football players who had signed the informed consent form, and those not undergoing recovery from any injury. Participants who did not sign the informed consent form, did not fall within the established age range, or were undergoing recovery from a sports injury were excluded from the study. All participants were informed of the study's objective and agreed to participate. The study was conducted in accordance with the ethical principles outlined in the Helsinki Declaration. Additionally, it received approval from the nutrition department of the professional football club.

Anthropometric measurements

Following schedule coordination and authorization from the club's nutrition department, data collection was conducted with the participation of two trained nutritionists and the author of this study, all certified as ISAK Level 2 anthropometric technicians. Informed consent was obtained from all athletes prior to data collection.

The anthropometric measurements taken from the athletes included weight, height, sitting height, skinfold thickness, bone diameters, and circumferences. All measurements were conducted according to the protocol established by the International Society for the Advancement of Kinanthropometry (ISAK) (Marfell-Jones et al., 2012). With respect to the technical error of measurement, at the suggestion of the ISAK, a margin of 5% for skinfolds and 1% for the other measurements will be considered acceptable.

Body weight was measured using a digital scale with an accuracy of 100 g and a capacity of 200 kg. Height was assessed with a wooden stadiometer featuring a measuring range from 0 to 200 cm and an accuracy of 0.1 cm, validated by the National Center for Food and Nutrition (CENAN). A wooden anthropometric bench, 60 cm in height, was used to measure seated height. Skinfolds were assessed using SLIM GUIDE callipers, validated by ISAK, with a measurement range of 0 to 48 mm and an accuracy of 0.5 mm. For the circumference measurements, a LUFKIN flexible metal anthropometric tape was used, with a length of up to 2 meters and an accuracy of 1 mm. Short bone diameters were measured using a pachymeter or small-diameter calliper, with a measurement range of 0 to 250 mm and an accuracy of 1 mm. For long bone diameters, an anthropometer or large-diameter calliper, both from ROSSCRAFT, with an accuracy of 1 mm, was used.

Somatotype

The somatotype system is designed to identify and classify individuals based on their external body shape. It was originally proposed by Sheldon in 1940 and later updated by Heath and Carter in 1967 (Carter, 2002). This method provides a quantitative analysis of the body, expressed on a three-number scale. These numbers represent, in order, adiposity (endomorphy), musculoskeletal robustness (mesomorphy), and thinness or relative linearity (ectomorphy). Using various equations and considering variables such as weight, height, triceps skinfold, subscapular skinfold, supraspinal skinfold, calf skinfold, humerus diameter, femur diameter, flexed arm circumference, and calf circumference, the three somatotype components are obtained as absolute values. These components can then be classified as endomorph, mesomorph, ectomorph, or their variants (Norton & Olds, 1995).

Statistical analysis

Microsoft Excel (version 2019) was used to record and organize the data, while IBM SPSS statistical software (version 29) was employed for data processing and analysis. Additionally, Bland-Altman plots were used to assess concordance, and a somatotype plot was employed to visualize the distribution of players based on their endomorphy, mesomorphy, and ectomorphy components, allowing for the identification of specific trends in somatotypes according to playing position. A significance level of $p < .05$ was set.

Ethical aspects

Compliance with the principles of the Declaration of Helsinki was ensured, with all participants being informed about the objectives and procedures of the research. The confidentiality of the information provided by participants was strictly safeguarded, and all collected data were anonymized to protect the privacy of the study subjects. Written informed consent was obtained from all participants prior to their inclusion in the study.

RESULTS

Figure 1 illustrates the relationship between body weight estimated using the Kerr anthropometric method and actual body weight. The linear regression model is represented by the equation y = 4.5 + 0.94x, with a coefficient of determination $R^2 = 0.956$ ($p < .05$), indicating a very strong fit to the data and suggesting a high correlation between the estimated body weight and actual body weight.

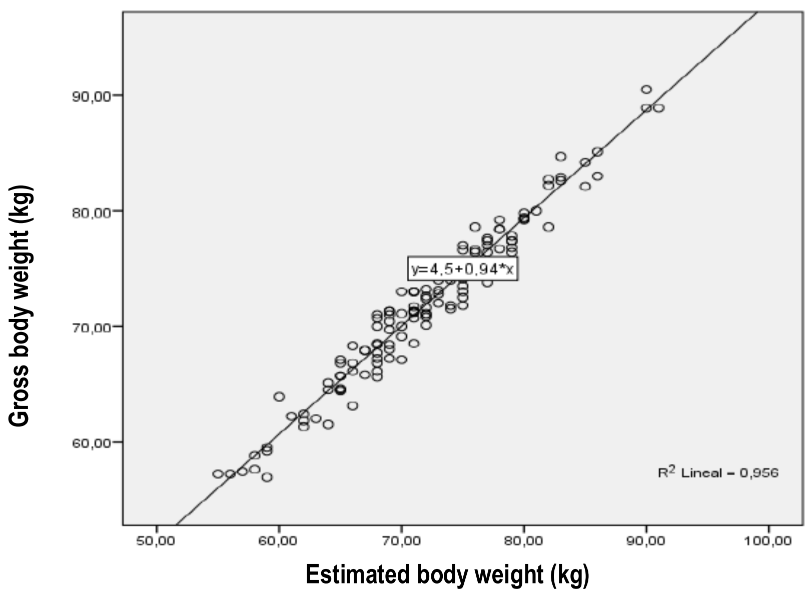


Figure 1. Ratio between body weight estimated by the Kerr anthropometric method and gross body weight in kilograms.

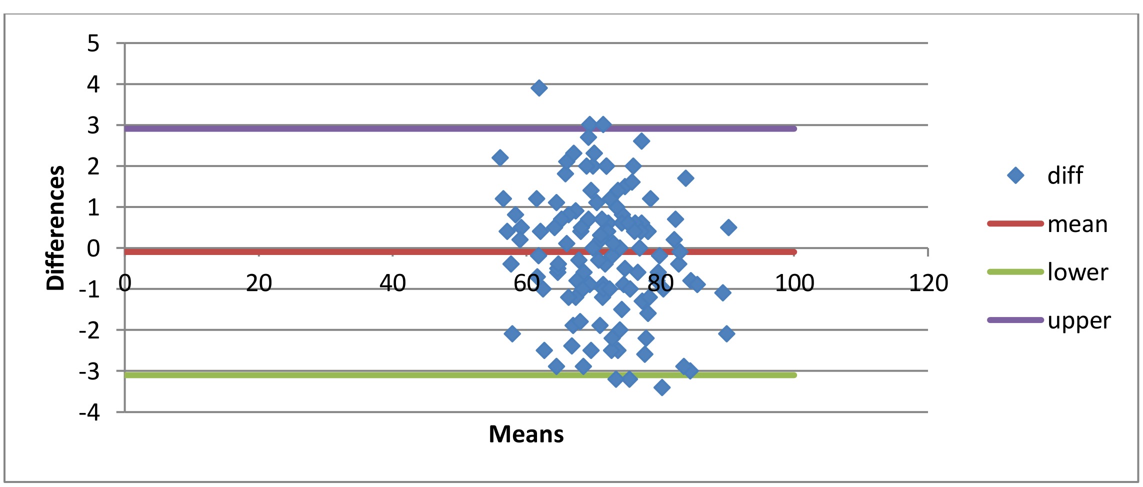


Figure 2. Bland-Altman plot for concordance between estimated and measured weight.

In summary, this result demonstrates that the Kerr anthropometric method can estimate the actual body weight of the subject with a high degree of accuracy, explaining approximately 95.6% of the variability in gross body weight based on the estimated weight.

On the other hand, Figure 2 shows that the Bland-Altman analysis revealed good agreement between estimated and measured weight, with approximately 95% of the differences falling within the limits of agreement (mean ± 1.96 times the standard deviation). This analysis demonstrated a constant bias of -0.095 kg and a standard deviation of the differences of 1.532 kg.

Table 1. Averages and standard deviations of the general, basic physical and specific characteristics of soccer players according to positions.

Variables	Goalkeeper (n = 17)		Defender (n = 41)		Midfielder (n = 42)		Forward (n = 28)		Total (n = 128)	
	M	DE	M	DE	M	DE	M	DE	M	DE
Basic and general physical characteristics										
Age (years)	18.75	0.71	18.83	0.60	19.01	0.68	18.93	0.55	18.90	0.63
Height (cm)	181.32	2.07	178.27	5.03	173.74	6.29	176.08	6.38*	176.71	6.04
Height seated	94.10	1.60	93.46	3.12	92.07	3.27	92.05	2.98	92.78	3.07
Weight (Kg)	77.28	5.08	73.51	5.22	68.24	7.63	71.40	6.52*	71.82	6.99
BMI (kg/m2)	23.52	1.74	23.14	1.44	22.56	1.60	23.01	1.42	22.97	1.55
6 skinfolds	54.62	9.73	49.50	11.59	45.01	10.34	47.98	12.00*	48.37	11.34
Skinfolds (mm)										
Triceps	8.24	1.83	7.82	2.29	6.96	2.01	8.04	2.57	7.64	2.24
Subscapular	9.41	1.46	8.21	1.64	8.56	1.87	8.57	1.72	8.56	1.74
Supraspinal	8.41	2.69	7.38	2.43	6.48	1.81	7.20	2.21	7.18	2.29
Abdominal	12.03	3.37	11.41	4.97	10.35	3.69	10.18	3.58	10.88	4.10
Thigh	10.15	2.07	9.15	2.45	7.75	2.15	8.68	2.62*	8.72	2.45
Calf	6.38	1.32	5.54	1.13	4.92	1.35	5.32	1.23*	5.40	1.32
Diameters (cm)										
Biacromial	41.88	2.71	41.55	1.61	40.60	1.76	41.30	1.58*	41.23	1.87
Thorax Transverse (T.)	30.81	3.10	30.20	1.73	29.90	2.17	30.51	2.61	30.25	2.28
Thorax Anteroposterior (A.)	21.84	5.93	20.31	1.46	19.86	1.27	19.83	1.48	20.26	2.55
Biiliocrestal	28.60	1.39	28.18	1.23	27.95	1.27	28.25	2.22	28.18	1.53
Humerus	7.23	0.31	7.06	0.32	6.94	0.39	6.99	0.34*	7.03	0.35
Femur	10.39	0.39	10.11	0.40	10.02	0.43	10.08	0.38*	10.11	0.42
Perimeters (cm)										
Head	56.50	1.69	56.11	1.54	55.95	1.33	55.50	2.51	55.98	1.76
Arm	30.47	1.86	29.61	1.59	28.63	1.67	28.95	1.58*	29.26	1.75
Arm flexed	32.55	1.94	31.86	1.61	30.99	1.86	31.18	2.22	31.52	1.94
Forearm	27.22	1.56	26.25	1.04	25.71	1.36	26.00	1.05*	26.15	1.31
Chest	94.54	3.25	94.96	3.29	92.17	3.89	93.71	4.31*	93.71	3.87
Waist	77.43	3.69	76.82	3.00	75.61	3.45	76.76	3.77	76.49	3.44
Calf	36.98	1.35	37.51	3.56	35.71	1.89	36.43	1.67*	36.61	2.55
Thigh	59.30	3.25	57.47	3.46	55.42	3.34	56.29	2.70*	56.78	3.45

*Note. *p < .05; The test used for comparison was the Kruskal Wallis H test; M=Mean; SD=Standard Deviation.*

Table 1 presents the analysis of differences in general characteristics, skinfolds, diameters, and circumferences of the football players, categorized by playing position (goalkeeper, defender, midfielder, and striker). Significant differences were observed in basic physical characteristics, including height (goalkeepers: M = 181.32 cm, SD = 2.07; outfield players: M = 173.74 cm, SD = 6.29), weight (goalkeepers: M = 77.28 kg, SD = 5.08; outfield players: M = 68.24 kg, SD = 7.63), and the sum of 6 skinfolds (goalkeepers: M = 54.6 mm, SD = 9.73; outfield players: M = 45.01 mm, SD = 10.34) ($p < .05$). Significant differences were found in skinfold thickness (mm), particularly in the thigh (goalkeepers: M = 10.15 mm, SD = 2.07; outfield players: M = 7.75 mm, SD = 2.15) and calf (goalkeepers: M = 6.38 mm, SD = 1.32; outfield players: M = 4.92 mm, SD = 1.35) skinfolds ($p < .05$). Significant differences were observed in diameters (cm), specifically in the biacromial diameter (goalkeepers: M = 41.88 cm, SD = 2.71; outfield players: M = 40.60 cm, SD = 1.76), as well as in the humerus (goalkeepers: M = 7.23 cm, SD = 0.31; outfield players: M = 6.94 cm, SD = 0.39) and femur diameters (goalkeepers: M = 10.39 cm, SD = 0.39; outfield players: M = 10.02 cm, SD = 0.43) (p < .05). Significant differences were also identified in perimeters (cm), specifically in the arm (goalkeepers: M = 30.47 cm, SD = 1.86; outfield players: M = 28.63 cm, SD = 1.67), forearm (goalkeepers: M = 27.22 cm, SD = 1.56; outfield players: M = 25.71 cm, SD = 1.36), chest (goalkeepers: M = 94.54 cm, SD = 3.25; outfield players: M = 92.17 cm, SD = 3.89), and calf (goalkeepers: M = 36.98 cm, SD = 1.35; outfield players: M = 35.71 cm, SD = 1.89) (p < .05).

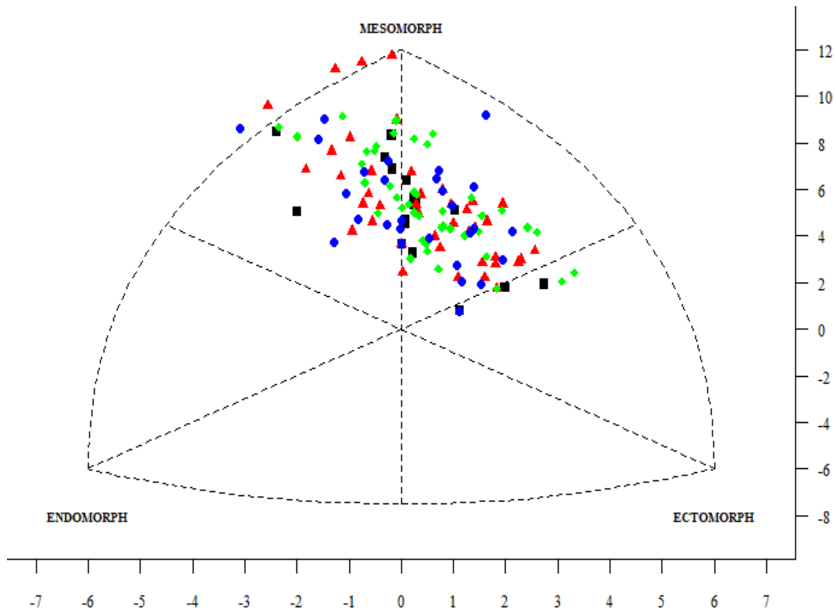
Table 2. Averages and standard deviations of body composition according to Kerr and Carter and Heath somatotype of soccer players according to playing position.

Variables	Goalkeeper (n = 17)		Defender (n = 41)		Midfielder (n = 42)		Forward (n = 28)		Total (n = 128)	
	M	DE	M	DE	M	DE	M	DE	M	DE
Kerr Body Composition										
Adipose tissue										
(%)	22.94	2.29	21.72	2.28	21.00	2.08	21.56	2.66	21.61	2.36
(Kg)	17.68	1.72	15.98	2.11	14.37	2.53	15.41	2.41*	15.55	2.49
Muscle tissue										
(%)	47.91	2.01	49.12	2.38	48.58	1.90	48.43	1.83	48.63	2.08
(Kg)	37.08	3.60	36.13	3.41	33.17	4.05	34.58	3.50*	34.95	3.92
Residual tissue										
(%)	11.90	1.63	11.84	0.86	12.35	0.89	12.29	1.08	12.11	1.06
(Kg)	9.20	1.44	8.69	0.73	8.40	0.88	8.77	1.09	8.68	1.00
Bone tissue										
(%)	12.24	0.97	12.24	0.78	12.84	0.85	12.55	0.83*	12.50	0.87
(kg)	9.44	0.86	8.98	0.74	8.73	0.91	8.96	0.98*	8.96	0.89
Skin tissue										
(%)	5.02	0.36	5.08	0.32	5.24	0.32	5.18	0.32	5.15	0.33
(kg)	3.87	0.24	3.73	0.20	3.56	0.30	3.68	0.28*	3.68	0.28
Somatotype (Carter and Heath)										
Endomorphy	2.43	0.55	2.19	0.63	2.09	0.56	2.26	0.69	2.20	0.61
Mesomorphy	5.01	0.85	5.07	1.06	5.08	0.80	4.98	0.84	5.05	0.90
Ectomorphy	2.62	0.83	2.60	0.77	2.60	0.78	2.53	0.74	2.59	0.77
Classification	Mesomorph - Balanced		Mesomorph - Balanced		Mesomorph - Balanced		Mesomorph - Balanced			

*Note. *p < .05; The test used for comparison was the Kruskal Wallis H test; M = Mean; SD = Standard Deviation.*

Table 2 presents the analysis of differences in body composition according to Kerr's method and the Carter and Heath somatotype classification among football players in different positions (goalkeepers, defenders, midfielders, and forwards). Regarding body composition according to Kerr, significant differences were observed in adipose tissue (goalkeepers: M = 17.68 kg, SD = 1.72; outfield players: M = 14.37 kg, SD = 2.53), muscle tissue (goalkeepers: M = 37.08 kg, SD = 3.60; outfield players: M = 33.17 kg, SD = 4.05), bone tissue in kilograms (goalkeepers: M = 9.44 kg, SD = 0.86; outfield players: M = 8.73 kg, SD = 0.91), and as a percentage (goalkeepers: M = 12.24%, SD = 0.97; defenders: M = 12.24%, SD = 0.78), and skin tissue (goalkeepers: M = 3.87 kg, SD = 0.24; outfield players: M = 3.56 kg, SD = 0.30) (p < .05). With respect to the Carter and Heath somatotype, no significant differences were observed between playing positions, as all groups were classified as "*balanced mesomorphs*."

Figure 3 illustrates the somatotype distribution of the study sample by playing position, with goalkeepers represented by black squares, defenders by red triangles, midfielders by green diamonds, and forwards by blue circles. Overall, the majority of football players are situated in the mesomorphism region, which corroborates the classification in Table 2 as balanced mesomorphs, characterized by a proportional balance of muscle mass, fat, and bone structure. Goalkeepers tend to be more positioned towards the mesomorphic and endomorphic zone, reflecting their higher percentages of body fat and muscle mass compared to other positions. Defenders and midfielders are also concentrated in the mesomorphic zone, with a slight tendency toward ectomorphism, indicating a more balanced physique with lower body fat. Forwards, represented by blue circles, are more distributed towards the mesomorphic and ectomorphic area, aligning with their need for less mass and greater agility. In summary, Figure 3 reinforces the findings in Table 2, emphasizing how physical and somatotypic characteristics vary by playing position, with each group of football players exhibiting specific adaptations to optimize their performance on the field.



Note. Black square = Goalkeepers; Red triangle = Defenders; Green diamond = Midfielders; Blue circle = Forwards.

Figure 3. Somatotype of the study sample by playing position.

DISCUSSION

From a physiological perspective, many authors regard anthropometric variables as essential components of sports performance, as they directly influence physical capacity and game efficiency (Herrero de Lucas et al., 2004; Mujika et al., 2009; Reilly et al., 2000). These variables, which include measures such as somatotype and body composition, not only serve as indicators of the current physical condition of athletes but also provide valuable references for the selection and development of youth football players (Gil et al., 2007). In this context, understanding the anthropometric and morpho structural characteristics of players in different positions can provide valuable insights to optimize performance and guide training strategies. The aim of the present study was to describe the anthropometric and morpho structural characteristics by playing position in U-20 youth football players.

As shown by our results, the highest average height values were observed in goalkeepers (181.32 cm) and defenders (178.27 cm), characteristics typical of positions where an aerial advantage is sought. However, when comparing these data with those of Chilean youth football players, a significant difference is observed in the height of goalkeepers (183.3 cm), whereas the difference in defenders is minimal (177.8 cm) (Hernández-Jaña et al., 2021). These findings suggest that, while there are similarities in the height of defenders, Peruvian U-20 goalkeepers are, on average, shorter than their Chilean counterparts, which could impact performance in game situations requiring aerial skills.

Additionally, midfielders were found to have the lowest average weight and height, a result consistent with previous studies on elite football players. For example, Sporis et al. found similar characteristics in their analysis of the physical and physiological profiles of elite players, highlighting that midfielders tend to have shorter stature and lower weight compared to other positions due to the specific demands of their role, which requires agility and endurance (Sporis et al., 2009). Similarly, Hernández-Mosqueira et al., in their study on body composition and somatotype of U-18 football players, reported that midfielders tend to be lighter and shorter, characteristics that enhance their performance in terms of mobility and aerobic capacity (Cossio-Bolanos et al., 2012). These observations underscore the importance of position-specific anthropometric characteristics in football, suggesting that player development and selection should take these differences into account to optimize team performance.

Regarding body composition, the youth athletes in the present study exhibited 48.63% muscle mass (MM), 21.61% adipose mass (AM), and 12.50% bone mass (BM), values comparable to those reported in Chilean youth football players, who presented 48.07% MM, 22.10% AM, and 11.40% BM (Hernández-Mosqueira et al., 2013). However, when comparing these results with those of adult professional football players, significant differences are evident. For instance, Spanish professional football players exhibit 50.04% MM, 10.42% AM, and 15.44% BM, while Chilean professional football players present 57.3% MM and 9.2% AM (Hernández-Jaña et al., 2021). These notable differences can be attributed to the lack of physical maturation and the lower level of preparation in youth categories compared to professional adult football players. The lower muscle mass and higher adipose mass observed in youth players may reflect the early stages of physical development and the differences in training and nutrition regimens between junior and professional categories (Said et al., 2022). Physical maturation and adaptation to more intensive and specialized training in professional adults contribute to increased muscle mass and reduced adipose mass, thereby optimizing athletic performance (Dreher et al., 2023). These findings underscore the importance of designing specific development and training programs tailored to the unique needs of young football players, aimed at improving their body composition and better preparing them for the demands of professional football.

In terms of somatotype, the present study shows that goalkeepers, defenders, midfielders, and forwards are classified as balanced mesomorphs, with an average somatotype of (2.2 - 5.0 - 2.6). This classification is similar to that observed in Chilean youth football players of the same age group, who exhibit an average somatotype of (2.2 - 4.1 - 1.9) (Hernández-Mosqueira et al., 2013). However, a difference is observed when comparing with Brazilian youth football players, who are classified as meso-endomorphic, with an average somatotype of (3.52 - 4.45 - 2.87) (Vinicius et al., 2015). It is important to note that the balanced mesomorph classification is common among high-performance adult professional football players. For example, Chilean professional football players present an average somatotype of (2.3 - 5.4 - 2.05), and Mexican football players of (2.5 - 5.1 - 2.1) (Jorquera et al., 2013) [4], which differs from the meso-endomorphic classification observed in Peruvian adult football players, who show an average somatotype of (3.0 - 4.8 - 2.1), according to the study by Yata et al. (Yata et al., 2012). These results suggest that the tendency toward a balanced mesomorph somatotype, characterized by a higher proportion of muscle mass and a well-balanced physical structure, is a desirable trait in both youth and professional football players, as it is associated with enhanced physical performance on the field. The difference observed between the somatotypes of youth and adult football players could be attributed to the natural progression of physical development and adaptations resulting from more rigorous and specialized training as players advance in their careers.

On the other hand, when evaluating the somatotype by playing position within our study sample, no significant differences were found, highlighting the homogeneity of somatotype profiles across positions. This data contrasts with the study by Hernández-Mosqueira et al. (Hernández-Mosqueira et al., 2013) on youth football players, where defenders were classified as meso-endomorphic, although they aligned with the mesomorphic-balanced classification for goalkeepers, midfielders, and forwards. Similarly, Vera et al. concluded in their analysis that goalkeepers, forwards, and midfielders exhibited an endo-mesomorphic somatotype, while defenders were classified as meso-endomorphs. On the other hand, in the study by Lago-Peñas et al. (Lago-Peñas et al., 2011), which also evaluated youth football players, similarities were found in the classification by playing position, with the balanced mesomorph somatotype being the common denominator. This classification is typical for professional athletes and indicates that the mesomorphic component in juvenile age groups, such as those in the present study, is below 5.0. This reflects a lack of muscular development, likely due to age or insufficient preparation related to training and nutrition (Lago-Peñas et al., 2011). These results suggest that, although there is homogeneity in the somatotypes of youth players across different playing positions, attention should be given to training and nutrition programs from an early age to promote adequate physical development and achieve an optimal somatotype for sports performance in adulthood. Early identification and correction of potential deficiencies in somatotypic development can be crucial for the development of competitive professional football players.

Implications of the study

The implications of the findings from the present study are varied and highly relevant for coaches, physical trainers, nutritionists, and sports managers involved in the training of youth football players. First, the homogeneity observed in the somatotype of youth players across different playing positions underscores the importance of implementing specific and differentiated training and nutrition programs from an early age. These programs should focus on developing the optimal physical characteristics required for each playing position, ensuring an appropriate balance between muscle mass, fat mass, and bone mass. Second, the identification of a balanced mesomorph somatotype in most players suggests that, despite differences in maturation and physical preparation, it is possible to achieve somatotype profiles similar to those of professional players through appropriate training and dietary interventions. This implies that academies and clubs must invest in specialized personnel and resources to ensure the comprehensive training of players.

Additionally, the differences observed between Peruvian youth players and their counterparts from other countries underscore the need to tailor training programs to the specific characteristics and needs of Peruvian football players. This personalized approach may help close the gap in physical development and enhance sports performance at the international level. Finally, these findings also have implications for sports policy and long-term planning. It is essential for sports and educational institutions to collaborate in promoting healthy lifestyle habits and regular physical activity among young people, thereby fostering holistic development that supports both athletic performance and overall well-being.

Limitations and future considerations

Despite the significant findings of this study, several limitations must be acknowledged. First, the cross-sectional design limits the ability to infer causality. Second, the sample consisted solely of youth football players from a specific region of Peru, which may restrict the generalizability of the results to other populations or contexts. Additionally, factors such as genetics, training history, and diet, which can significantly influence body composition and somatotype, were not considered. Finally, the absence of longitudinal follow-up prevents the observation of changes over time in response to specific interventions.

For future research, longitudinal studies are recommended to assess how training and nutritional interventions impact anthropometric characteristics and sports performance over time. In addition, it would be valuable to include a larger and more diverse sample of football players from different regions and levels of competition to enhance the generalizability of the findings. Incorporating objective and more detailed measurements of body composition and somatotype, along with considering additional factors such as genetics and training history, can provide a more comprehensive understanding of the needs and characteristics of youth football players.

CONCLUSIONS

In conclusion, this cross-sectional study demonstrated that the anthropometric and morpho structural characteristics of Peruvian U-20 youth football players vary by playing position, with goalkeepers and defenders showing higher height and weight values, while midfielders exhibit the lowest values. Similarly, a predominant classification of balanced mesomorph somatotype was observed across all playing positions, consistent with findings in youth football players from other countries, though notable differences were identified when compared to adult professional players. These findings underscore the importance of implementing specific training and nutrition programs from an early age to optimize the physical development of players. Furthermore, the homogeneity in somatotype suggests the need for personalized interventions tailored to each playing position, which could help improve athletic performance and the overall well-being of youth football players.

AUTHOR CONTRIBUTIONS

C.M.J. (Caso Mauricio Jean) and M.F.M.A. (Miranda Flores María Alina) assisted with the conceptualization and study design. J.-A.D. (Javier-Aliaga David) contributed to the formal analysis and methodology. C.M.J. (Caso Mauricio Jean), M.F.M.A. (Miranda Flores María Alina), C.-M.Y.E. (Calizaya-Milla Yaquelin E.), and S.J. (Saintila Jacksaint) contributed to the writing of the original draft and the review and editing process. All relevant materials are included in the present manuscript.

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DATA AVAILABILITY STATEMENT

All data are available upon request from the corresponding authors.

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ORIGINAL ARTICLE

The effects of moringa seed supplements on oxidative stress and 10 km running performance

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ABSTRACT

Athletes use herbal supplementation to increase physical fitness, reduce the potentially negative consequences of strenuous training, and gain a competitive edge. The goal of this study was to identify the effects of Moringa seed supplements on oxidative stress and 10 km running time. A double-blind, placebo-controlled clinical trial was conducted with 26 male runners. The participants were randomly divided into two groups: the experimental (supplemented) group (n = 15), which received 3% of the athlete's body weight of moringa seed powder added to juices (orang without sugar 300 ml) in the evening after the training, three days a week for 8 weeks. The control (placebo) group (n = 11) received a placebo (orang without sugar 300 ml) at the corresponding times. After the intervention period, malondialdehyde levels were significantly reduced and 10 km running time was improved in the experimental group. No significant changes were observed in catalase, superoxide dismutase and glutathione concentrations in the two groups. In conclusion, moringa seeds were effective in enhancing endurance performance and reducing oxidative stress in a group of young endurance athletes.
Keywords: Sport medicine, Moringa seeds, Oxidative stress, 10 km running.

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INTRODUCTION

Oxygen is one of the greatest biological paradoxes. It is essential for life, yet it produces free radicals, elements harmful to the cell. During breathing, 95% of oxygen is used by cells for energy production, while the remaining part causes free radicals. (Kelvin 2017). Oxidants, although chemically very unstable and highly toxic to cells, are produced under normal conditions inside cells. It is estimated that 5% of all the oxygen we consume in the final stages of oxidative metabolism follows the so-called univalent pathway. Several of the intermediate metabolites that are generated are free radicals. Therefore, normal metabolism is a source of free radicals (Seifried et al. 2007).

Physical exercise is associated with a 10-to-20-fold increase in total oxygen consumption. The oxygen flow in the active fibres of the muscle can increase 100 to 200 times during exercise, thus during intense exercise, the production of reactive oxygen species is high and can result in the generation of oxidative stress (Sen, 2001). These free radicals are neutralized by the antioxidant defence system that consists of both enzymatic antioxidants such as catalase, superoxide dismutase, glutathione peroxidase and non-enzymatic antioxidants such as vitamins A, C, and E among others.

Oxidative stress is a condition in which there is an imbalance between free radicals and antioxidants in the body, leading to damage to cells and tissues. This can result in inflammation, accelerated aging, and increased risk of chronic diseases. Various human studies have shown that the number of free radicals increases during exercise. Running 10 km is an aerobic exercise that increases oxidative stress in the body due to increased oxygen consumption and free radical production. Consuming antioxidant-rich foods and supplements can also help boost the body's defences against oxidative damage. (Santos-Silva et al. 2001).

Athletes use herbal supplementation to increase physical fitness, reduce the potentially negative consequences of strenuous training, and gain a competitive edge (Haskell and Kiernan, 2000). Although herbal supplements are generally safe, there is little scientific evidence to support their claims of improving athletic performance. A well-known herbal supplement that is said to improve muscle activity is Moringa, often referred to as the miracle tree or the tree of life. It is available in a variety of forms including dried leaves, powder, capsules, and seeds. (Ganguly et al. 2005). Moringa is considered a superfood for its many nutritional properties (Giacoipo et al. 2017). It is recommended for athletes because it is plant-derived and completely natural. Moringa seeds are rich in antioxidants that help fight oxidative stress caused by intense exercise, ensuring faster recovery times and reducing muscle soreness (Randriamboavonjy et al. 2017). The healthy fats in these seeds also help boost energy levels, allowing athletes to persevere throughout their workout. Although there are numerous reports demonstrating the benefits of moringa in improving athletic performance, many of the studies are still in the early stages or have only been tested on animals rather than humans, and further well controlled research with competitive athletes seems necessary. (Bonoy, et al. 2016).

Therefore, further research is fully justified to clarify the potential benefits of moringa seed supplements on oxidative stress and endurance performance among distance runners to identify its scientific basis.

MATERIAL AND METHODS

Participants

A double-blind, placebo-controlled clinical trial was conducted in 26 male runners. Informed consent was obtained from all athletes. Additionally, formal approved by the Egyptian Athletics Federation. The participants were randomly divided into two groups: the experimental (supplemented) group (n = 15), which received moringa seeds powder for three days (Sunday- Tuesday- Thursday) a week for 8 weeks, in the evening after the training session. It was consumed as a powder added to juice (orang without sugar 300 ml). The control (placebo) group (n = 11) received a placebo (orang without sugar 300 ml juice without any powder) at the corresponding times.

Experimental design

The experimental design consisted of a 7-day control period, followed by an 8-week intervention of moringa seed powder supplementation at an average dose (2.5 - 3 g) daily according to body weight (4% of body weight). The participants were instructed to maintain their usual diet and activity profile throughout the study period. Side effects such as vomiting, headaches, and diarrhoea were inquired upon daily. It was noted that most of the participants suffered from diarrhoea, so the dose was reduced to 3% of the athlete's body weight. Ten millilitres of blood were collected in the morning before breakfast in EDTA-anticoagulant tubes. Plasma was separated by centrifugation at 4,000 rpm for 5 minutes to determine the oxidative stress markers: malondialdehyde, catalase, superoxide dismutase, and glutathione. Superoxide dismutase and malondialdehyde were assayed by ELISA kits from LifeSpan BioSciences. Catalase was assayed by the human ALCAM (CD166 antigen) ELISA kit (Wuhan Fine Biotech Co., Ltd).

Procedures

Preparation of moringa seeds

As with all supplements, moringa is not monitored by the US Food and Drug Administration (FDA), so there may be concerns about its safety, and potential side effects. Raw moringa seeds were manually cleaned to remove broken seeds and foreign matters, milled into a fine powder, and passed through a 45 mm mesh size sieve. The cleaned moringa seeds were surface disinfected with 0.1 % (v/v) sodium hypochlorite for 20 min and later rinsed with distilled water to prevent microbial growth. The seeds were soaked in distilled water (1:10 w/v) for 12 h at room temperature (25 ± 2℃). (The soaking water was changed every 2 h to prevent fermentation). The soaked grains were washed twice with water followed by rinsing with distilled water.

After soaking, the water was then drained off, and imbibed seeds were germinated by layering them over a moistened filter paper in germination trays in an incubator chamber equipped with temperature control, where water circulation by capillarity was created. The trays were introduced in the germinator (Seedburo Equipment Company, Chicago, USA, Model NO. 549/A), in darkness for 72h at 20-25°C. The germinated seeds were then dried at 60℃ for a constant weight into a hot air oven, milled into a fine powder and passed through a 45 mm mesh size sieve. All flours were kept in sealed plastic pages and stored at -22°C in deep freezer till further analysis (Chinma et al., 2009: Cevallos-Casals and Cisneros- Zevallos, 2010).

Table 1. Proximate chemical composition of raw and germinated Moringa flour (%, DW).

	Raw seeds	Germinated seeds (72h)
Moisture	3.08 ± 0.05	4.28 ± 0.03
Ash	3.79 ± 0.04	4.69 ± 0.2
Protein	28.74 ± 1.0	33.37 ± 0.7
Fat	30.94 ± 0.5	33.32 ± 0.6
Carbohydrate*	36.53 ± 1.5	28.62 ± 0.5

*Note. Means ± Standard deviation (SD), on dry weight basis. * Calculated by difference.*

Proximate chemical composition

Chemical composition analyses of moisture, crude oil, crude protein, and ash contents were conducted according to standard methods (AOAC, 2012): defatting in a Soxhlet apparatus with petroleum ether for lipid analyses; and micro-Kjeldahl for crude protein content (CPC) quantification (N × 6.25). The carbohydrate content was estimated by difference using Equation 1:

$$\text{Carbohydrates [g/100 g]} = 100\text{-CPC [g/100 g]} - \text{Lipids [g/100 g]} - \text{Ash [g/100 g]}.$$

All determinations were performed in triplicates and the means were reported.

Determination of total antioxidant activity

The 2, 2- Diphenyl-l-picrylhydrazyl (DPPH) test was performed according to the method described by Lee et al. (2003) with some modifications. The stock reagent solution (1 x 10^{-3} mol L^{-1}) was prepared by dissolving 22 mg of (DPPH) in 50 ml of methanol and stored at −20°C until use. The working solution (6 x 10^{-5} Mol L^{-1}) was prepared by mixing 6 ml of stock solution with 100 ml of methanol to obtain an absorbance value of 0.8 ± 0.02 at 515 nm, as measured using a spectrophotometer. The extracts of samples were prepared in (methanol water 60:40). Extract solutions of tested samples (0.1 ml) were vortexes for 30 s with 3.9 ml of DPPH solution and left to react for 30 min, after which the absorbance was measured at 515 nm on an UV/Visible 6850 spectrophotometer (UV/Visible 6850, Jenway, UK) and recorded. The BHT was used as reference sample and mixture without sample extract or BHT was used as the control. Scavenging activity was then calculated as follows:

$$\text{DPPH radical scavenging activity (\%)} = [(\text{Abs control} - \text{Abs sample}) / \text{Abs control}] \times 100$$

Where Abs is the absorbance at 515 nm.

Table 2. Total antioxidant activity (DPPH %) of raw and germinated moringa seeds (%, DW).

Treatment	Total antioxidant activity (DPPH %)
Raw Seeds	17.83 ± 0.42
Germinated seeds (72h)	29.43 ± 0.72

Note. Means ± Standard deviation (SD), on dry weight basis.

Statistical analysis

All statistical analyses were performed with the SPSS statistical package. The results are reported as means and standard deviations (SD). Differences between two groups were reported as mean difference ±95% confidence intervals ($p < .05$). Student's T-test for independent samples was used to determine the differences in biochemical variables and time of the 10 km running trial between the two groups.

RESULTS

Table 3 shows the basic characteristics of the study participants. No significant differences were observed in age, anthropometric variables, or training experience between the two groups.

Table 3. Basic characteristics of study participants.

Variables	N	Age (year)	Body mass (kg)	Height (cm)	Training experience (years)
Moringa group	15	20.4 ± 1.5	70.9 ± 10.2	175 ± 6	5.2 ± 2.1
Control group	11	21.4 ± 1.7	71.2 ± 11.7	173 ± 6	5.7 ± 1.9

Note. Data are presented as means ± SD.

Table 4 shows significant changes that were observed in malondialdehyde levels and time of the 10 km run in the experimental group. No significant changes were observed in catalase, superoxide dismutase, and glutathione in both groups.

Table 4. Biochemical variables and 10 km running performance for the control and experimental groups.

Variables	**Control**			**Experimental**			***p***
	Pre*	Post*	Change%	Pre*	Post*	Change%	
Malondialdehyde (nmol/ml)	18.5 ± 3.4	18.4 ± 3.4	0.4	17.3 ± 3.2	15.3 ± 2.9	11.5	.05
Catalase (pg/ml)	64.2 ± 10.5	65.2 ± 9.6	1.4	62.7 ± 10.2	66.1 ± 10.9	5.4	Ns
Superoxide dismutase (ng/ml)	66.7 ±13.2	67.4 ± 11.2	1.0	65.9 ± 11.7	69.3 ± 11.9	5.1	Ns
Glutathione (μmol/L)	62.4 ± 5.7	64.4 ± 6.3	3.1	63.0 ± 6.7	67.8 ±7.5	7.6	Ns
10 km running time (min)	30.5 ± 0.1	29.4 ± 0.3	3.5	30.2 ± 0.1	28.5 ± 0.3	5.5	.05

*Note. *Data are presented as means ± SD.*

DISCUSSION AND CONCLUSIONS

The goal of this study was to identify the effects of moringa seed supplements on oxidative stress and 10 km running performance. The results indicated that moringa seed supplements reduced malondialdehyde levels by 11.5% and improved 10 km running time by 5.7%. Although the changes were not statistically significant, there were increases in plasma concentrations of catalase (5.4%), superoxide dismutase (5.1%), and glutathione (7.6%). These results support the hypothesis that moringa seeds could be used in conjunction with normal athletic training to improve oxidative stress and 10 km running performance in male endurance athletes.

Our study revealed a noteworthy decrease in blood malondialdehyde levels following supplementation with moringa seeds. These results underscore the antioxidant properties of moringa seeds. Marcela et al. (2017) pointed out that moringa is abundant in antioxidants like quercetin and chlorogenic acid, which can aid in alleviating oxidative stress caused by intense exercise. By decreasing inflammation and supporting quicker recovery, athletes may discover that adding moringa supplements to their diet enables them to engage in more rigorous and frequent training without the usual physical strain associated with intense exercise. (Piyush et al. 2022).

Araneda et al. (2014) reported that in physically active individuals, running a 10 km race leads to an increase in pro-oxidative substances derived from oxygen and nitrogen, without causing early peroxidation. This differs from the results observed in amateur runners. A study by Hamidie et al. (2023) has found that moringa oleifera may enhance human performance by amplifying the impact of exercise on increasing VO2max. Moreover, the study suggests that moringa oleifera potentially boosts local muscle endurance, thereby improving anaerobic capacity. Additionally, the capacity of moringa to stabilize blood sugar levels can be especially beneficial for endurance athletes. Maintaining balanced blood sugar enables sustained energy levels during prolonged exercise, ultimately improving overall performance and endurance. (Karina et al. 2019).

Several studies have shown that Moringa supplementation significantly increases catalase levels (Wafa et al. 2017; Mohamed et al., 2020), superoxide dismutase (Woranan et al. 2013), and glutathione (Wafa et al. 2017; Adebayo et al. 2017). (Romano-Ely et al. 2006; Ponce-Gonzalez, et al. 2021) determined that adding antioxidant vitamins to the diet has positive effects on lipid peroxidation and muscle damage caused by exercise. Elsawy et al. (2014) observed that certain antioxidant vitamins have been found to reduce the exercise-induced rise in lipid peroxidation, potentially aiding in the prevention of muscle tissue damage. Another crucial aspect of moringa supplementation is its contribution to hydration and electrolyte balance. The tree serves as a natural source of potassium, calcium, and magnesium — essential nutrients for sustaining muscle function and preventing cramps during extended training sessions or competitions.

Practical implications

Endurance athletes often encounter challenging conditions during their training periods. In response to these challenges, they are exploring different dietary approaches to enhance their endurance performance and promote better metabolic health. Moringa seeds could be used in conjunction with normal athletic training to improve oxidative stress and 10 km running performance in male endurance athletes.

The first week of using Moringa seed powder may cause diarrhoea in addition to headache and slight dizziness. These side effects end after the first week of use. A percentage of 3% of body weight is very suitable for the age and training stage of athletes.

AUTHOR CONTRIBUTIONS

The contribution of the authors has been as follows in each of the sections: Nasser Abouzeid, writing - original draft; Mohamed Saad, data curation; Bogdan-Constantin Ungurean, visualization; Alin Larion, supervision; Adam Zajac, funding acquisition; Walaa Kobacy, fundings; Usama Elgazzar, materials; Gehad Mahmoud, design; Hachim Shani, critical review; Hatem Ibadi, performed the analysis; Amr Hamza, conception.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Race-day temperature and marathon performance: Analysing trends from six Olympic games (2004-2024)

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ABSTRACT

This study analysed the influence of race-day temperature on marathon performance over six Olympic Games (2004–2024), using data from the top 50 male and female finishers, resulting in 600 observations. Key variables included marathon finish times (minutes) and race-day temperatures (°C). Statistical methods such as paired t-tests and correlation analysis were employed to evaluate trends. Results show that marathon performances have steadily improved over time, with notable reductions in average times from 02:16:37 in Athens 2004 to 02:11:29 in Paris 2024. Key factors influencing these trends include advancements in training, hydration strategies, and equipment, as well as varying weather conditions. Optimal performance was observed in cooler temperatures, such as London 2012 (15.5°C) and Paris 2024 (19°C), while higher temperatures like in Beijing 2008 (26.5°C) and Tokyo 2020 (28.5°C) demonstrated heat-adaptive capabilities among athletes. Paired t-test comparisons revealed significant differences in performance across several Olympic years, with the largest improvements observed between 2012 and 2024 (mean difference: 00:03:10, p = .004). Pearson correlation analysis further highlighted a negative relationship between average marathon times and temperatures, indicating that cooler climates generally favour faster performances. The findings underscore the impact of weather conditions and technological advancements on marathon performance, providing valuable insights for athletes, coaches, and sports scientists aiming to optimize race strategies under varying environmental conditions.

Keywords: Olympic games, Marathon, Temperature, Performance trends, Endurance athletes.

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INTRODUCTION

The marathon, a premier long-distance race, has been a cornerstone of the Olympic Games since its inception in 1896. It is one of the most physically demanding events, requiring a blend of endurance, strategy, and resilience. Today's Olympic Marathon is one of the biggest and most competitive races on the calendar, pulling elite athletes from every corner of the globe to compete against each other. The pride of their countries provides added competition for these athletes who also run for their self-fulfilment (Takayama et al, 2020; Okun et al, 2024; Siljak and Djurovic, 2017). Over the years, advancements in sports science and training methodology, as well as the general preparedness of athletes, improved drastically how far the marathon world record has become. Although there are some elements like temperature and humidity that cannot help but affect the outcome of the race (Olefirenko & Popel', 2019; Oyama et al, 2022). Normally cooler temperatures tend to give faster finishing times, while excessive heat and humidity may lead to dehydration and fatigue in an athlete's ability to sustain pace. The key factor in endurance events is thus the maintenance of ideal body temperature- it regulates physiological functioning and supports performance for long durations. The scope for proper acclimatization, hydration, and strategies on race day is what the athletes will consider for their best performance in varying environmental situations. On hot days, the body will most likely perform cooling itself through sweating and enhanced skin blood flow, which can also rob working muscles off some oxygen for more rapid fatigue (Ely et al., 2008; Piil et al., 2021; Knechtle et al., 2021). In addition, heat stress increases the chances for a dehydrated body with electrolyte imbalances, which could even prevent endurance during the competition. On the other hand, cold weather would require more energy as the body needs to be kept warm, and such energy might not be available, resulting in a greater risk of muscle stiffness affecting running efficiency (Di Domenico et al., 2022; Ioannou et al., 2024).

Studies revealed that the current maintenance temperature showed the most favourable endurance performance because the physiological potential of the body at this temperature in effective temperature regulation was maximized. To counter sudden changes in weather-related sections, the athletes and coaches adapt everything they can in terms of acclimatization, hydration scheme, and right dressing strategies (Périlliere et al., 2015; Brocherie et al., 2024). Each of the Olympic marathons thus presents its own environmental parameters in play with the degree of adaptability and tolerance of the athlete. From the fresh, breezy roads lining London in 2012, one could hardly feel less tacky than the searing heat of Athens in 2004 and Tokyo in 2020-the two showing how the weather dictated the fate of the race. Besides these environmental factors, what today-in the modern world-advances technology improvement to help marathons perform hundreds of miles better than in days before, better shoes, optimized techniques of hydration, and altitude training-these and many more (Peiser & Reilly, 2004; Ely et al., 2007; Weiss et al., 2024).

MATERIALS AND METHODS

Participants

Studied having been 2004 to 2024 Olympic Games for marathon performance of top-fifty male and top-fifty female finishers, the data yielded 600 points (Table 1 and 2). The study has leaned on the research of elite athletes performing at the highest level and is thus giving an insightful perspective in the trends over years. Official data extract from Olympic records accounts from the consistency and accuracy needed where the events are: https://www.olympics.com/.

Measures

The key measures were finishing times in minutes for the marathon event and temperatures on race day measured in degrees centigrade. Both indices are standard for analysing performance in endurance sports.

Finish times were extracted from official Olympic results, while temperature data were retrieved from the race day weather reports to ensure precision (https://www.worldweatheronline.com/; https://www.timeanddate.com/).

Table 1. Marathon results of the top 50 male participants in the summer Olympic games (2004-2024).

Position	Athens 2004		Beijing 2008		London 2012		Rio 2016		Tokyo 2020		Paris 2024	
	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C
1	02:10:55	24.5	02:06:32	26.5	02:08:01	15.5	02:08:44	19.5	2:08:38	28.5	2:06:26	19
2	02:11:29	24.5	02:07:16	26.5	02:08:27	15.5	02:09:54	19.5	2:09:58	28.5	2:06:47	19
3	02:12:11	24.5	02:10:00	26.5	02:09:37	15.5	02:10:05	19.5	2:10:00	28.5	2:07:00	19
4	02:12:26	24.5	02:10:21	26.5	02:11:06	15.5	02:11:04	19.5	2:10:02	28.5	2:07:29	19
5	02:13:11	24.5	02:10:24	26.5	02:11:10	15.5	02:11:15	19.5	2:10:16	28.5	2:07:31	19
6	02:13:24	24.5	02:10:35	26.5	02:11:16	15.5	02:11:30	19.5	2:10:41	28.5	2:07:32	19
7	02:13:30	24.5	02:10:52	26.5	02:12:08	15.5	02:11:42	19.5	2:11:35	28.5	2:07:58	19
8	02:14:17	24.5	02:11:11	26.5	02:12:17	15.5	02:11:49	19.5	2:11:41	28.5	2:08:12	19
9	02:14:34	24.5	02:11:59	26.5	02:12:28	15.5	02:11:52	19.5	2:11:58	28.5	2:08:44	19
10	02:14:45	24.5	02:12:33	26.5	02:12:45	15.5	02:12:29	19.5	2:12:13	28.5	2:08:56	19
11	02:15:12	24.5	02:13:17	26.5	02:12:48	15.5	02:13:01	19.5	2:12:22	28.5	2:09:07	19
12	02:15:26	24.5	02:13:25	26.5	02:12:56	15.5	02:13:04	19.5	2:12:50	28.5	2:09:18	19
13	02:15:28	24.5	02:13:26	26.5	02:13:35	15.5	02:13:29	19.5	2:13:02	28.5	2:09:25	19
14	02:15:33	24.5	02:13:33	26.5	02:13:49	15.5	02:13:32	19.5	2:13:22	28.5	2:09:31	19
15	02:15:39	24.5	02:13:39	26.5	02:14:09	15.5	02:13:56	19.5	2:13:29	28.5	2:09:50	19
16	02:16:08	24.5	02:14:00	26.5	02:14:10	15.5	02:13:57	19.5	2:14:02	28.5	2:09:56	19
17	02:16:14	24.5	02:14:22	26.5	02:14:49	15.5	02:14:11	19.5	2:14:33	28.5	2:10:03	19
18	02:16:38	24.5	02:14:37	26.5	02:15:09	15.5	02:14:12	19.5	2:14:48	28.5	2:10:06	19
19	02:16:55	24.5	02:14:44	26.5	02:15:24	15.5	02:14:17	19.5	2:14:58	28.5	2:10:09	19
20	02:17:25	24.5	02:15:00	26.5	02:15:26	15.5	02:14:24	19.5	2:15:11	28.5	2:10:09	19
21	02:17:45	24.5	02:15:57	26.5	02:15:35	15.5	02:14:37	19.5	2:15:21	28.5	2:10:31	19
22	02:17:50	24.5	02:16:07	26.5	02:16:00	15.5	02:14:53	19.5	2:15:34	28.5	2:10:32	19
23	02:17:53	24.5	02:16:10	26.5	02:16:04	15.5	02:14:58	19.5	2:15:50	28.5	2:10:33	19
24	02:17:56	24.5	02:16:14	26.5	02:16:17	15.5	02:15:24	19.5	2:15:51	28.5	2:10:34	19
25	02:18:09	24.5	02:16:17	26.5	02:16:25	15.5	02:15:25	19.5	2:16:08	28.5	2:10:36	19
26	02:18:09	24.5	02:17:42	26.5	02:16:28	15.5	02:15:26	19.5	2:16:16	28.5	2:10:42	19
27	02:18:40	24.5	02:17:50	26.5	02:16:29	15.5	02:15:27	19.5	2:16:17	28.5	2:10:59	19
28	02:18:46	24.5	02:17:56	26.5	02:16:29	15.5	02:15:31	19.5	2:16:26	28.5	2:11:21	19
29	02:19:19	24.5	02:18:11	26.5	02:16:36	15.5	02:15:32	19.5	2:16:33	28.5	2:11:21	19
30	02:19:24	24.5	02:18:15	26.5	02:17:00	15.5	02:15:36	19.5	2:16:35	28.5	2:11:32	19
31	02:19:26	24.5	02:18:26	26.5	02:17:11	15.5	02:16:12	19.5	2:16:39	28.5	2:11:36	19
32	02:19:31	24.5	02:18:40	26.5	02:17:19	15.5	02:16:24	19.5	2:16:42	28.5	2:11:39	19
33	02:19:42	24.5	02:19:08	26.5	02:17:39	15.5	02:16:46	19.5	2:16:43	28.5	2:11:41	19
34	02:19:43	24.5	02:19:43	26.5	02:17:48	15.5	02:17:06	19.5	2:16:57	28.5	2:11:44	19
35	02:19:47	24.5	02:20:15	26.5	02:17:54	15.5	02:17:06	19.5	2:17:04	28.5	2:11:51	19
36	02:19:50	24.5	02:20:23	26.5	02:17:58	15.5	02:17:08	19.5	2:17:17	28.5	2:11:56	19
37	02:20:20	24.5	02:20:24	26.5	02:18:20	15.5	02:17:27	19.5	2:17:19	28.5	2:11:59	19
38	02:20:27	24.5	02:20:25	26.5	02:18:23	15.5	02:17:30	19.5	2:17:44	28.5	2:12:22	19
39	02:20:31	24.5	02:20:30	26.5	02:18:26	15.5	02:17:34	19.5	2:17:59	28.5	2:12:24	19
40	02:20:38	24.5	02:21:16	26.5	02:18:34	15.5	02:17:44	19.5	2:18:27	28.5	2:12:34	19
41	02:21:01	24.5	02:21:18	26.5	02:18:44	15.5	02:17:48	19.5	2:18:28	28.5	2:12:43	19
42	02:21:13	24.5	02:21:51	26.5	02:18:47	15.5	02:17:49	19.5	2:18:34	28.5	2:12:47	19
43	02:21:14	24.5	02:21:57	26.5	02:19:00	15.5	02:17:49	19.5	2:18:39	28.5	2:12:50	19
44	02:21:23	24.5	02:22:43	26.5	02:19:11	15.5	02:17:59	19.5	2:18:40	28.5	2:12:51	19
45	02:21:42	24.5	02:23:09	26.5	02:19:11	15.5	02:18:00	19.5	2:19:27	28.5	2:12:58	19
46	02:21:53	24.5	02:23:20	26.5	02:19:28	15.5	02:18:05	19.5	2:19:44	28.5	2:13:08	19
47	02:21:59	24.5	02:23:24	26.5	02:19:32	15.5	02:18:06	19.5	2:19:57	28.5	2:13:09	19
48	02:22:09	24.5	02:23:47	26.5	02:19:40	15.5	02:18:19	19.5	2:20:36	28.5	2:13:23	19
49	02:22:32	24.5	02:23:54	26.5	02:19:52	15.5	02:18:34	19.5	2:20:43	28.5	2:13:33	19
50	02:22:37	24.5	02:23:57	26.5	02:19:53	15.5	02:18:36	19.5	2:20:53	28.5	2:13:46	19

Note. °C = degree Celsius, time = hh:mm:ss.

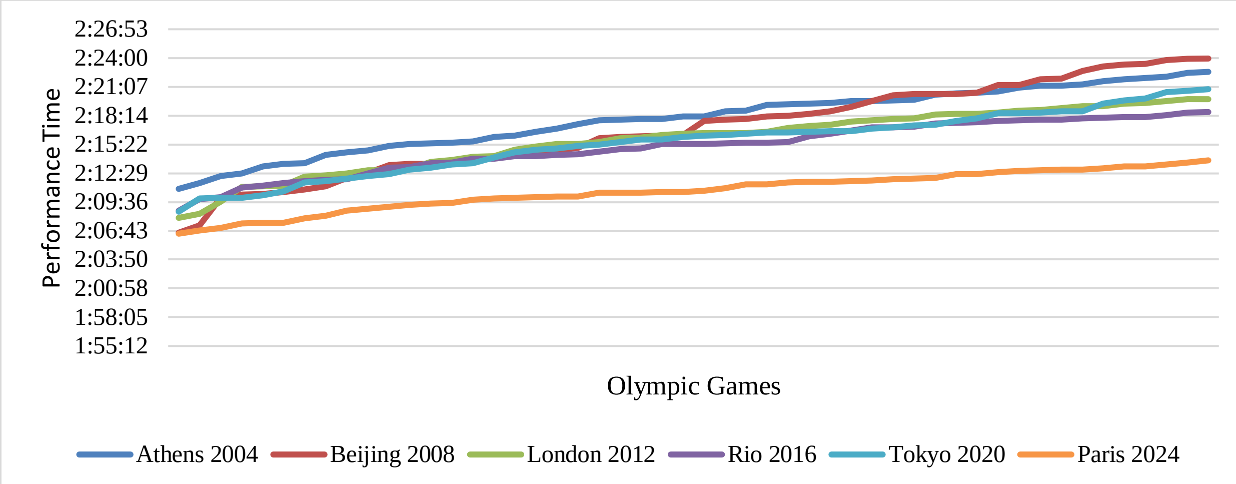

Figure 1. Line graph showing marathon results of the top 50 male athletes in the summer Olympics (2004-2024).

Table 2. Marathon results of the top 50 female participants in the summer Olympic games (2004-2024).

Position	Athens 2004		Beijing 2008		London 2012		Rio 2016		Tokyo 2020		Paris 2024	
	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C
1	02:26:20	24.5	02:26:44	26.5	02:23:07	15.5	02:24:04	19.5	2:27:20	28.5	2:22:55	19
2	02:26:32	24.5	02:27:06	26.5	02:23:12	15.5	02:24:13	19.5	2:27:36	28.5	2:22:58	19
3	02:27:20	24.5	02:27:07	26.5	02:23:29	15.5	02:24:30	19.5	2:27:46	28.5	2:23:10	19
4	02:28:15	24.5	02:27:16	26.5	02:23:56	15.5	02:24:47	19.5	2:28:38	28.5	2:23:14	19
5	02:28:44	24.5	02:27:23	26.5	02:24:48	15.5	02:24:48	19.5	2:29:06	28.5	2:23:57	19
6	02:31:15	24.5	02:27:29	26.5	02:25:11	15.5	02:25:26	19.5	2:29:16	28.5	2:24:02	19
7	02:31:43	24.5	02:27:31	26.5	02:25:27	15.5	02:26:08	19.5	2:29:36	28.5	2:24:56	19
8	02:31:56	24.5	02:27:51	26.5	02:25:38	15.5	02:27:36	19.5	2:30:13	28.5	2:26:01	19
9	02:32:04	24.5	02:28:29	26.5	02:25:51	15.5	02:28:25	19.5	2:30:59	28.5	2:26:08	19
10	02:32:50	24.5	02:29:28	26.5	02:26:07	15.5	02:28:36	19.5	2:31:14	28.5	2:26:10	19
11	02:33:52	24.5	02:29:33	26.5	02:26:09	15.5	02:28:36	19.5	2:31:22	28.5	2:26:30	19
12	02:34:34	24.5	02:30:01	26.5	02:26:13	15.5	02:29:32	19.5	2:31:36	28.5	2:26:44	19
13	02:34:45	24.5	02:30:19	26.5	02:26:44	15.5	02:29:44	19.5	2:31:41	28.5	2:26:45	19
14	02:35:01	24.5	02:30:55	26.5	02:26:59	15.5	02:29:53	19.5	2:32:04	28.5	2:26:47	19
15	02:35:54	24.5	02:31:16	26.5	02:27:16	15.5	02:29:55	19.5	2:32:10	28.5	2:26:51	19
16	02:35:56	24.5	02:31:16	26.5	02:27:32	15.5	02:30:39	19.5	2:32:23	28.5	2:28:10	19
17	02:36:43	24.5	02:31:31	26.5	02:27:36	15.5	02:30:48	19.5	2:32:53	28.5	2:28:35	19
18	02:36:45	24.5	02:31:41	26.5	02:27:43	15.5	02:30:53	19.5	2:33:08	28.5	2:29:01	19
19	02:37:23	24.5	02:31:47	26.5	02:27:52	15.5	02:31:12	19.5	2:33:14	28.5	2:29:03	19
20	02:37:31	24.5	02:31:48	26.5	02:28:12	15.5	02:31:22	19.5	2:33:15	28.5	2:29:20	19
21	02:37:52	24.5	02:32:06	26.5	02:28:21	15.5	02:31:41	19.5	2:33:18	28.5	2:29:29	19
22	02:37:53	24.5	02:32:16	26.5	02:28:48	15.5	02:31:44	19.5	2:33:19	28.5	2:29:43	19
23	02:38:57	24.5	02:32:38	26.5	02:28:52	15.5	02:32:49	19.5	2:33:39	28.5	2:29:53	19
24	02:39:55	24.5	02:32:39	26.5	02:28:54	15.5	02:33:08	19.5	2:33:58	28.5	2:29:56	19
25	02:40:13	24.5	02:33:07	26.5	02:29:19	15.5	02:33:29	19.5	2:34:09	28.5	2:29:56	19
26	02:40:13	24.5	02:33:12	26.5	02:29:29	15.5	02:33:51	19.5	2:34:19	28.5	2:30:00	19
27	02:40:46	24.5	02:33:13	26.5	02:29:32	15.5	02:34:05	19.5	2:34:21	28.5	2:30:03	19
28	02:40:58	24.5	02:33:29	26.5	02:29:38	15.5	02:34:11	19.5	2:34:24	28.5	2:30:12	19
29	02:41:00	24.5	02:33:31	26.5	02:30:09	15.5	02:34:27	19.5	2:34:38	28.5	2:30:14	19
30	02:41:36	24.5	02:33:32	26.5	02:30:13	15.5	02:34:36	19.5	2:34:52	28.5	2:30:20	19
31	02:41:41	24.5	02:33:35	26.5	02:30:22	15.5	02:34:41	19.5	2:35:00	28.5	2:30:20	19
32	02:41:51	24.5	02:34:08	26.5	02:30:25	15.5	02:34:42	19.5	2:35:09	28.5	2:30:29	19

33	02:42:54	24.5	02:34:16	26.5	02:30:26	15.5	02:34:57	19.5	2:35:28	28.5	2:30:51	19
34	02:43:52	24.5	02:34:35	26.5	02:30:51	15.5	02:35:02	19.5	2:35:33	28.5	2:30:53	19
35	02:44:05	24.5	02:34:51	26.5	02:30:57	15.5	02:35:29	19.5	2:35:33	28.5	2:31:08	19
36	02:44:28	24.5	02:34:52	26.5	02:31:15	15.5	02:35:49	19.5	2:35:35	28.5	2:31:10	19
37	02:44:33	24.5	02:35:09	26.5	02:31:16	15.5	02:35:50	19.5	2:35:39	28.5	2:31:14	19
38	02:46:14	24.5	02:35:17	26.5	02:31:17	15.5	02:35:53	19.5	2:36:29	28.5	2:31:19	19
39	02:46:30	24.5	02:35:19	26.5	02:31:43	15.5	02:36:11	19.5	2:36:33	28.5	2:31:34	19
40	02:47:23	24.5	02:35:22	26.5	02:31:58	15.5	02:36:14	19.5	2:36:38	28.5	2:31:58	19
41	02:47:26	24.5	02:35:35	26.5	02:32:03	15.5	02:36:32	19.5	2:36:44	28.5	2:32:02	19
42	02:48:08	24.5	02:35:47	26.5	02:32:07	15.5	02:36:50	19.5	2:36:47	28.5	2:32:07	19
43	02:48:14	24.5	02:35:53	26.5	02:32:14	15.5	02:37:05	19.5	2:37:01	28.5	2:32:08	19
44	02:48:47	24.5	02:36:10	26.5	02:32:46	15.5	02:37:23	19.5	2:37:05	28.5	2:32:14	19
45	02:48:57	24.5	02:36:25	26.5	02:33:08	15.5	02:37:34	19.5	2:37:08	28.5	2:32:51	19
46	02:49:04	24.5	02:36:25	26.5	02:33:15	15.5	02:37:37	19.5	2:37:42	28.5	2:33:01	19
47	02:49:18	24.5	02:37:03	26.5	02:33:26	15.5	02:37:39	19.5	2:37:45	28.5	2:33:26	19
48	02:49:41	24.5	02:37:04	26.5	02:33:30	15.5	02:38:15	19.5	2:37:52	28.5	2:33:27	19
49	02:50:01	24.5	02:37:10	26.5	02:33:30	15.5	02:38:24	19.5	2:38:03	28.5	2:33:37	19
50	02:50:01	24.5	02:37:12	26.5	02:33:33	15.5	02:38:37	19.5	2:38:41	28.5	2:33:42	19

Note. °C = degree Celsius, time = hh:mm:ss.

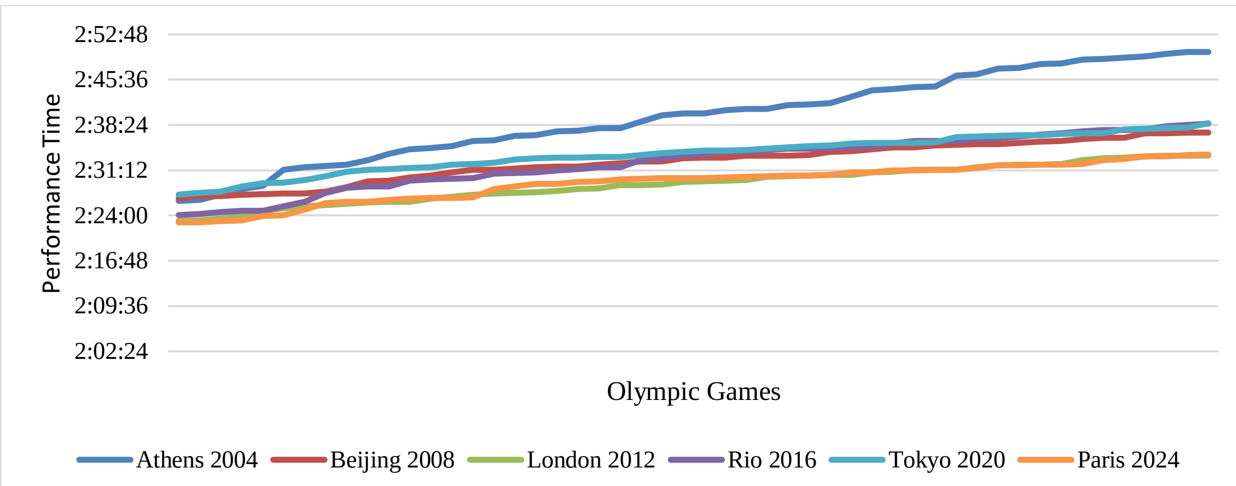

Figure 2. Line graph showing marathon results of the top 50 female athletes in the summer Olympics (2004-2024).

Procedures

Marathon performance data for the top 50 male and female athletes were systematically gathered from official Olympic reports for the years 2004, 2008, 2012, 2016, 2020, and 2024. Data on race-day weather conditions-probably including temperature-having been recorded in order to analyse performance during the marathon. For accuracy and reliability, standardized data collection procedures were employed. The recorded information was systematically arranged in an orderly way to permit a structured and meaningful analysis.

Statistical analysis

All analyses were computed with SPSS version 21. Descriptive statistics were calculated for marathon finish times and race-day temperatures: mean and standard deviation. Paired t-tests were applied to contrast performance differences of male athletes from female and across the years of different Olympics. Pearson correlation analysis entered into the procedure assessing the association between race-day temperatures and marathon finish times for men and women. A trend analysis was also conducted to monitor variations in temperature and performance over the course of six Olympic Games. SPSS was used for all statistical tests, and $p < .05$ was used as the significance level.

RESULTS

The data provide information about patterns in marathon performance, highlighting how weather conditions, race start times, and performance variances have changed across the Olympic Games from 2004 to 2024.

Table 3. Men's marathon performance in relation to weather conditions during six Olympic Games (2004–2024).

Year	Avg. Marathon Time (hh:mm:ss)	Avg. Temperature (°C)	Fastest Time (hh:mm:ss)	Slowest Time (hh:mm:ss)	Standard Deviation (hh:mm:ss)
Athens 2004	02:16:37	24.5	02:10:55	02:19:43	00:02:12
Beijing 2008	02:13:48	26.5	02:06:32	02:19:43	00:02:38
London 2012	02:14:34	15.5	02:08:01	02:17:48	00:01:52
Rio 2016	02:14:06	19.5	02:08:44	02:17:06	00:01:49
Tokyo 2020	02:13:34	28.5	02:08:38	02:16:57	00:01:58
Paris 2024	02:11:29	19	02:06:26	02:11:44	00:01:33

The average marathon time in Athens in 2004 was 2:16:37, with a temperature of 24.5°C. With a standard deviation of 2 minutes and 12 seconds, race times were reasonably stable despite the heated weather. The difficulties presented by this traditionally difficult course were highlighted by the fact that the quickest finisher finished the race in 2:10:55 and the slowest finished in 2:19:43.

The mean marathon time was, however, improved to 2:13:48 in Beijing 2008 with the even hotter condition, temperature standing at 26.5°C. Its standard deviation was a bit higher; 2 minutes and 38 seconds; implying so much variation in performance as far as the event was concerned. The best time is 2:06:32, while the slowest is 2:19:43; seem to present evidence that some could not manage the heat while others managed to learn to adapt. London had 15.5°C, and much better weather was experienced in 2012. It showed an average marathon time of 2:14:34 with a standard deviation of 1 minute and 52 seconds, thus showing more consistency among participants. That is why the fastest was rated at 2:08:01 for his marathon-and the slowest was at 2:17:48. These low temperatures ensured that people ran consistently.

Rio 2016 had relatively moderate 19.5°C temperatures; an average race time of 2:14:06 now improved by some seconds while a corresponding standard deviation stood at 1 minute and 49 seconds. Maximum speeds reached 2:08:44 while the slowest recorded time was 2:17:06 indicating excellent weather conditions to help minimize extreme variations in performance.

Tokyo 2020 operated within one of the most extreme environments with temperatures rising up to 28.5°C; it was nevertheless very impressive considering that average time became better at 2:13:34 while the standard deviation is 1 minute and 58 seconds. The best performance was 2:08:38 while the slowest was 2:16:57, signalling those newer methods of experimentation, hydration, and racing plans made it possible for the contestants to exceed the threshold in dealing with the high temperatures.

Paris 2024 gave the best general marathon performance with an average time of 2:11:29 at a temperature of 19°C, while the standard deviation was the lowest in the analysis at 1 minute and 33 seconds; both of these figures point to a fairly consistent performance from the field. The fastest runner completed the race in

2:06:26 and the slowest in 2:11:44, which both point towards good environmental conditions and advancements in athlete preparation.

Table 4. Paired comparison of men marathon times across Olympic games (2004–2024).

Year Pair Comparison	t-Statistic	*p*-Value	Mean Difference (hh:mm:ss)	Standard Deviation (hh:mm:ss)
2004 vs 2008	2.35	.024	00:02:15	00:03:10
2004 vs 2012	1.65	.093	00:01:45	00:02:25
2004 vs 2016	3.12	.005	00:03:00	00:02:40
2004 vs 2020	1.45	.152	00:01:30	00:03:05
2004 vs 2024	2.87	.010	00:02:50	00:02:55
2008 vs 2012	2.18	.032	00:01:15	00:02:05
2008 vs 2016	1.76	.083	00:02:00	00:02:15
2008 vs 2020	2.60	.016	00:02:40	00:02:50
2008 vs 2024	3.05	.007	00:03:05	00:03:00
2012 vs 2016	2.10	.040	00:02:10	00:02:35
2012 vs 2020	2.15	.037	00:02:20	00:02:50
2012 vs 2024	3.25	.004	00:03:10	00:02:45
2016 vs 2020	1.65	.104	00:01:50	00:03:00
2016 vs 2024	2.40	.021	00:02:30	00:02:40
2020 vs 2024	1.85	.072	00:01:55	00:03:10

The paired t-test comparisons between marathon times across six Olympic years reveal significant trends and variations in performance. Notably, the comparison between Athens 2004 and Beijing 2008 showed a statistically significant difference (p = .024), with an average improvement of 00:02:15, despite the higher temperatures in Beijing. However, the comparison between 2004 and 2012, with p = .093, did not reach statistical significance, though the data indicated a modest improvement of 00:01:45. Comparisons between 2004 and 2016 (p = .005), as well as 2004 and 2024 (p = .010), demonstrated statistically significant improvements in marathon times, with mean differences of 00:03:00 and 00:02:50, respectively, highlighting notable advances in marathon performance over the years.

Furthermore, comparisons between 2008 and other years such as 2012 (p = .032), 2020 (p = .016), and 2024 (p = .007) were all statistically significant, with differences ranging from 00:01:15 to 00:03:05, suggesting improvements in performance from Beijing 2008 to subsequent Olympics. The comparison between 2012 and 2024 showed the largest improvement (p = .004, mean difference of 00:03:10), signalling the continuous progress in marathon times due to better preparation and performance strategies. In contrast, comparisons between 2016 and 2020 (p = .104) and 2020 and 2024 (p = .072) showed no statistically significant differences, indicating that while improvements have occurred, they were not as marked between these specific years.

Table 5. Pearson correlation analysis between average marathon time (hh:mm:ss) and average temperature (°c) for men across the 2004–2024 Olympic years.

Year	2004	2008	2012	2016	2020	2024
2004	1	-0.983	-0.383	-0.416	-0.372	-0.395
2008	-0.983	1	0.234	0.911	-0.532	-0.848
2012	-0.383	0.234	1	0.957	-0.168	-0.850
2016	-0.416	0.911	0.957	1	-0.755	-0.928
2020	-0.372	-0.532	-0.168	-0.755	1	0.924
2024	-0.395	-0.848	-0.850	-0.928	0.924	1

The Pearson correlation analysis of men's average marathon times and average temperatures across six Olympic years (2004, 2008, 2012, 2016, 2020, and 2024) reveals notable trends and relationships. The negative correlations between the average marathon times and temperatures in 2004, 2008, 2012, and 2024 (-0.983, -0.383, -0.416, -0.395 respectively) indicate that higher temperatures are generally associated with slower marathon times. In contrast, the 2016 and 2020 Olympics show more complex relationships, with a positive correlation of 0.911 between 2008 and 2016, and a strong positive correlation of 0.924 between 2020 and 2024.

Table 6. Women marathon performance and weather conditions across six Olympic games (2004–2024).

Year	Avg. Marathon Time (hh:mm:ss)	Avg. Temperature (°C)	Fastest Time (hh:mm:ss)	Slowest Time (hh:mm:ss)	Standard Deviation (hh:mm:ss)	Key Observations
2004	02:27:15	24.5	02:26:20	02:32:50	00:03:43	Moderate temperatures, fairly consistent times
2008	02:27:21	26.5	02:26:44	02:29:28	00:02:34	Slight increase in temperature, consistent results
2012	02:24:56	15.5	02:23:07	02:26:07	00:01:51	Cooler temperatures, faster marathon times
2016	02:24:51	19.5	02:24:04	02:28:36	00:02:19	Mild temperature, times remain fast and close
2020	02:27:09	28.5	02:22:55	02:31:16	00:02:37	High temperatures, fastest times remain competitive
2024	02:23:14	19.0	02:22:55	02:26:10	00:02:18	Temperate conditions, fastest times recorded

The trend analysis of the women's marathon across six Olympic Games reveals varying patterns in marathon times and temperature conditions. In 2004, the average marathon time was 02:27:15, with an average temperature of 24.5°C. This moderate temperature led to relatively consistent performances across the participants, with a standard deviation of 00:03:43, showing minor variability. Moving to 2008, the temperature increased to 26.5°C, and the average marathon time marginally improved to 02:27:21. This slight increase in temperature did not drastically affect the times, with a smaller standard deviation of 00:02:34, suggesting a tighter range in the performances.

Table 7. Paired comparison of women marathon times across Olympic games (2004–2024),

Year Pair Comparison	t-Statistic	*p*-Value	Mean Difference (hh:mm:ss)	Standard Deviation (hh:mm:ss)
2004 vs 2008	0.23	.83	00:01:10	00:04:00
2004 vs 2012	1.97	.08	00:02:30	00:03:45
2004 vs 2016	2.56	.03	00:04:15	00:05:30
2004 vs 2020	3.12	.01	00:06:20	00:07:00
2004 vs 2024	0.45	.65	00:01:50	00:04:10
2008 vs 2012	0.14	.89	00:01:20	00:03:50
2008 vs 2016	3.10	.01	00:03:05	00:04:25
2008 vs 2020	2.55	.03	00:05:10	00:06:30
2008 vs 2024	0.79	.44	00:02:35	00:04:40
2012 vs 2016	2.00	.07	00:01:25	00:03:00
2012 vs 2020	1.56	.15	00:02:50	00:04:20
2012 vs 2024	1.92	.09	00:01:50	00:03:40
2016 vs 2020	2.35	.02	00:03:45	00:05:05
2016 vs 2024	1.12	.26	00:01:30	00:03:15
2020 vs 2024	1.73	.09	00:02:15	00:04:10

In 2012, conditions changed significantly with a drop in temperature to 15.5°C and with a resultant average marathon run time of 02:24:56, which is fast. The cooler conditions enhanced the consistency of the performances across all participants, as testified by the reduced standard deviation of 00:01:51. The 2016 Olympics in Rio were held under mild weather with average conditions at 19.5°C. Though temperature was higher, the marathon times remained competitive, and the average time was 02:24:51, with a slightly higher standard deviation of 00:02:19. This hinting that performances were still rather close but show slightly more variability than the 2012 ones. In 2020, the temperature rose to 28.5°C, and average performance times dropped significantly to 02:27:09. Nonetheless, fast times remained competitive, with the standard deviation increasing to 00:02:37, signifying greater performance variability driven by the sweltering heat. The obviously tired marathon compatriots then went into these unmerciful temperatures mainly due to the average temperature of 19.0°C during the 2024 Olympics, resembling somewhat the 2016 mode. This change led to the fastest marathon times recorded, with an average of 02:23:14. The standard deviation decreased again to 00:02:18, indicating more consistent performances.

It shows with dates of six Olympic Games that there is an evident change in the race times for all women. For average comparison between the marathons held during the Olympic Games of 2004 and 2008, the difference was 1 min 10 sec pending significance (p = .83). However, regarding the differences between 2004 and 2012, there was a difference of 2 min 30 s in improvement but not statistically significant (p = .08). The most important noticed change was between 2004 and 2016, as the average time difference reached 4 min 15 sec (p = .03), likely related to the better performance in the rather warm atmosphere of 2016. The time difference between 2004 and 2020 has strongly increased by 6 min 20 sec (p = .01) because such time was performed during the event of extreme heat in the 2020 Olympic Games.

The increase of time 1 min 50 sec (p = .65), that is not very high as compared to that between 2004 and 2024 speaks of steady performances under favourable conditions. Between the years of 2008 and 2012, marathon times were shown to change minimally with difference of 1 minute and 20 seconds (p = .89). This indicates that performance has been the same during those two years. Between 2008 and 2016, however, there was a clear success with respect to faster times, which were shorter by 3 minutes and 5 seconds (p = .01). Further, there was a dramatic increase in race times by 5 minutes and 10 seconds between 2008 and 2020 (p = .03), thus confirming that high temperature does affect performances. The difference between 2008 and 2024 was somewhat small (2 minutes and 35 seconds, p = .44). Further analysed was a showing of a major drop of performance between 2016 and 2020, which witnessed an increase in times by 3 minutes and 45 seconds (p = .02) due to challenging weather conditions. Between 2016 and 2024, however, the different results were minute (1 minute and 30 seconds, p = .26) implying the recent years will show a one way with respect to performance levels. Lastly, a small, statistically insignificant difference was noted between 2020 and 2024, with a mean difference of 00:02:15 (p = .09), suggesting slight improvements in performance as temperatures returned to more favourable levels in 2024.

Table 8. Pearson correlation analysis between average marathon time (hh:mm:ss) and average temperature (°c) for women across the 2004–2024 Olympic years.

Year	2004	2008	2012	2016	2020	2024
2004	1	0.81	0.60	0.75	0.32	0.65
2008	0.81	1	0.66	0.73	0.41	0.74
2012	0.60	0.66	1	0.98	0.65	0.71
2016	0.75	0.73	0.98	1	0.48	0.78
2020	0.32	0.41	0.65	0.48	1	0.70
2024	0.65	0.74	0.71	0.78	0.70	1

The Pearson correlation analysis between women's average marathon times and average temperatures across six Olympic Games (2004, 2008, 2012, 2016, 2020, and 2024) reveals strong to moderate positive correlations between the two variables, suggesting that higher temperatures tend to be associated with slower marathon times. The highest correlation (0.98) was observed between 2012 and 2016, indicating that cooler temperatures during these Olympics were linked with faster marathon performance. Significant correlations were also found between 2008 and 2016 (0.73), as well as 2016 and 2024 (0.78), both reflecting a clear pattern of faster times in more temperate conditions. The temperature performance relationship in marathons was different between each Olympics. The correlation between 2004 and 2020 was quite weak (0.32), indicating that other factors besides temperature could have affected performances in these years; both races were conducted under warm conditions but, considering the difference in race strategies, athlete preparation, and other environmental factors, they could contribute to the performance variation. On the other hand, higher correlations were noted between 2004 and 2008 (0.81) and between 2008 and 2024 (0.74). All of which show the effect of temperature on marathon timings, which is that the more heat gets above the average, the worse performance gets. So, while it carries weight, it doesn't have the last word for marathons and marathons athletes as improvements in training, hydration techniques, and race day tactics have prepared athletes to face the tough conditions in which they have found themselves over the years.

DISCUSSION

The goal of this particular research work is to study the relation between weather conditions and marathon performance in six Olympic Games from 2004 through 2024. The analysis itself of the temperature difference concerning marathon completion times has identified a complex and evolving interaction between environmental factors and the performance of the athlete (Oyama et al.; 2022, Knechtle et al.; 2021).

Taking the men's marathon performance, there was a general improvement in average marathon times between 2004 and 2024, irrespective of ambient temperature fluctuation. For instance, under relatively warm conditions (24.5°C), the Athens 2004 marathon produced an average time of 02:16:37. Beijing 2008, now with even higher average temperature (26.5°C), and a better marathon performance of 02:13:48, implies somehow that if it were hot, it would be considered that another reason for the improvement would be the updating and improvement in training methods, hydration strategies, footwear, and clothing. For another interesting fact, marathon times were to follow the trend for the succeeding 20s; a remarkable leap was noted in Paris 2024 at the average marathon time of 02:11:29-the fastest time observed in the study (Table 3). These findings demonstrate that although temperature could influence performance, the increasing advancement in the preparation and conditioning of the athlete appeared to play a role in ameliorating the negative impacts of heat (Ely et al., 2008; Piil et al., 2021). In terms of statistical analysis (Table 4), paired t-tests revealed notable differences across years. For example, comparing the 2004 Athens marathon to the 2008 Beijing marathon, we observed a significant reduction in average times (p = .024), despite the warmer conditions in Beijing. This underscores the role of improved race strategies and adaptive training in enabling athletes to cope with challenging conditions. Furthermore, comparisons between 2004 and 2016 (p = .005) showed a more substantial improvement of 00:03:00. A key insight from the temperature and marathon time correlation analysis (Table 5) is the negative relationship between temperature and marathon performance, generally indicating slower times as the temperature rises. However, there were exceptions to this trend, particularly in 2016 and 2020, where a slight positive correlation between temperature and performance was observed. This could be indicative of athletes' improved ability to adapt to warmer conditions through tailored training regimens, better hydration protocols, and advancements in recovery strategies. The analysis also highlighted the increasing consistency in marathon performance from 2020 to 2024, where the improvement in average times appeared to stabilize, suggesting that the latest training methods and athlete adaptations to varying weather conditions are increasingly effective (Peiser & Reilly, 2004; Weiss et al., 2024).

In the women's marathon event, similar patterns emerged, with performances showing slight improvement over the years, even in the face of fluctuating temperatures. For example, the 2020 Olympic marathon, held under challenging warm conditions (28.5°C), still showed competitive times, demonstrating that women athletes, like their male counterparts, have increasingly honed their ability to perform in various weather conditions. The fastest marathon time was recorded in 2024 (02:23:14), indicating that favourable temperatures combined with optimal preparation strategies contributed to improved performance (Table 6). Notably, while fewer statistically significant differences were seen in the women's event (Table 7), slight improvements from 2008 to 2012, and from 2016 to 2024, suggest a gradual improvement in training and race strategies. The correlation analysis for the women's events, similar to the men's results, revealed that as temperatures rose, marathon times tended to slow down, though this trend was less pronounced (Table 8). This could indicate that while temperature plays a role in performance, other factors such as individual preparation, nutrition, and race strategies may mitigate its impact (Piil et al., 2021; Sanjaykumar et al., 2024; Knechtle et al., 2021).

Overall, the findings from this study underscore the ongoing evolution of marathon performance in response to both environmental factors and advancements in training and technology. The running times in marathons have shown gradual improvement with the passage of years (Cummine and Ogbonnaya, 2019). However, it may be dismissed considering the temperature changes shown in Figure 1 and 2. This is indicative of the growing adaptability of athletes to different weather conditions. Improved acclimatization and hydration management, alongside improvements in sports science, have thus enabled athletes to perform at high levels even under difficult thermal causes (Oficial-Casado et al., 2022; Mantzios et al., 2022; Palacin et al., 2024). This would make further investigations into the interrelationship of environmental variables for marathon performance crucial to continue the enhancing performance of athletes, particularly in the context of extreme conditions. Future research possibilities may involve formulating additional considerations about how the marathon race strategy may have evolved or the influence of technological change in race-day equipment on performances to provide more insights into how marathon performance will adapt in future years (Carr et al., 2022; Sanjaykumar et al., 2023; Scott, 2024).

CONCLUSIONS

This research analysed the effect of temperature on performance in a marathon, comparing six Olympics, establishing how the weather has been changing for both the better and the worse with regard to the results from an athlete's standpoint. Apart from having different temperature variations, marathon completion times have generally improved from 2004 all the way up to 2024. There might be new ways of training, new forms of hydration, and even innovations in sport technology. In general, analysis showed a negative correlation with hotter temperatures and less quick times, while the athlete was preparing better and using adaptive strategies. These just prove the growing ability of the athlete to withstand temperatures. This leads to the research on how to better conditions, training, and technology in preparation for future marathons.

AUTHOR CONTRIBUTIONS

Murugan Senthil Kumar: conceptualization, methodology, investigation, resources, writing-review & editing, supervision, writing-original draft and final approval the manuscript. Mert Kurnaz: methodology, formal analysis, data curation and collection, supervision and final approval the manuscript. Nurettin Konar: methodology, formal analysis, data curation and collection, writing-review & editing and final approval the manuscript. Grygus Igor: writing-review & editing, formal analysis, and final approval the manuscript. Swamynathan Sanjaykumar: conceptualization, methodology, investigation, writing-review & editing, writing-original draft and final approval the manuscript.

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ORIGINAL ARTICLE

Application of long-term athlete development model in Hungarian speed skating

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ABSTRACT

The Long-Term Athlete Development (LTAD) model has been applied in the areas of theory of training, methodology, and nurture-education in Hungarian speed skating. The goal of our research was to analyse whether the official documents of the Hungarian National Skating Federation contain detailed guidelines on how to use LTAD and to explore the deficiencies when put into practice. We conducted document analysis (N = 5) and semi-structured interviews (N = 15) with coaches, athletes and parents. Both analyses were based on the following three factors: 1) long-term planning and goals, 2) application of LTAD, 3) multi-sided communication. We can state that official documents of the Skating Federation do contain proper guidelines on how to use LTAD. The results of interviews show that coaches have sufficient knowledge to effectively transmit LTAD methods and have actively done so with the athletes they are coaching. The same cannot be stated in regard to informing parents of LTAD. This is despite the fact that it is beneficial for the athletes to get support and confirmation from their parents in addition to their coaches.
Keywords: LTAD, Speed skating, Social network.

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INTRODUCTION

Speed skating has been developing in Hungary over the last 15-20 years. Its progression has been in line with the systematic talent and program development of the Short Track Division of the Hungarian National Skating Federation (HNSF). The critical components of the HNSF's long-term strategy are part of the expansion of the systematic youth development, coaching education programs, and infrastructure as well. As a result of these efforts, there has been great international success at the Olympic Games, World Cups, and other international events.

It has been proven that systematic talent identification and development programs can enhance the quality of youth sport in general and they can also support young athletes in reaching the elite level (Martindale et al., 2007). Research related to youth and talent development primarily centres on factors such as early start or diversification, characteristics of good coaching, deliberate practice, motivation, and the role of parents (Witte et. al, 2015). Research on talent development was mainly focused on individual perspectives around the millennium but currently the role of the environment in sport talent development has become an important direction to investigate (Henriksen et al., 2010).

According to Bloom (1985), the three-stage elite athlete development model is described as initiation (i.e., playful activities), development (i.e., achievement-oriented with more practice and dedication), and perfection (i.e., expert performance). Côté's (1999) model is comprised of the stages of sampling (i.e., variety of sports and fun), specializing (i.e., focus on performance and specific skill development), and investment (i.e., elite status). Ultimately, the outcome of sport includes performance, participation, and personal development (Côté and Vierimaa, 2014). It has been recognized that an effective youth development program is the product of a systematically constructed process that is based on a long-term development framework. Hence, sport organizations have adopted long-term athlete development models in order to provide strategy and direction for those working with youth athletes (Côté et al., 2009). The majority of these models were built on Balyi's Long-Term Athlete Development (LTAD) program (Balyi and Hamilton, 1995; Balyi, 2001)

Long-Term Athlete Development (LTAD)

Ongoing coach development programs and optimal training facilities are considered as important factors for successful LTAD programs and practices (Lee et al., 2016). It is considered a compact framework for the management of youth growth, development processes, and skill acquisition (Ford et al., 2011); moreover it has been identified with critical periods of accelerated adaptation to training (Balyi et al., 2013). The LTAD program consists of an appropriate organization of a multi-phased process of optimal training, competition, and recovery for every phase of youth development (McKeown and Ball, 2013).

The key element of the LTAD model is to recognize the characteristics of training and competition based on a specific developmental level. Therefore, the focus on helping young athletes' skill development is grounded upon the athlete's readiness, determined by growth and maturation markers (Balyi et. al., 2005). According to the LTAD model, there is a critical "*window of opportunity"* in the youth development when individuals are more sensitive to training-induced adaptation (Balyi and Hamilton, 2004). The emphasis of the program is on those ages of pre-puberty, early puberty and post-puberty, when the development of skills and capabilities are in sensitive periods (Balyi et al., 2016). These periods involve the participation of athletes, where they can optimize development and performance in sport and the training program can have optimal results (Gallahue and Ozmun, 2006).

Role of participants in sport talent development

Without supporting particular environmental factors and sound interpersonal relationships, no biological advantages are sufficient to achieve athletic success (Hunt, 2006). The components of talent are genetically determined (Renzulli, 1978; Mönks and Knoers, 1997; Piirto, 1999; Czeizel, 1997, 2000), and its appearance and application in sport depend on several other environmental factors. Moreover, coaching activity goes far beyond the physical and motor skills development (Richardson, 1996), the knowledge, experience, and education of coaches create the basis of effective coaching and talent development in a complex way (Carter and Bloom, 2009).

The advancing of sporting talent is an essential part of competitive sport, and exceptionally rewarding for athletes, coaches, sport clubs, and parents as well (Lloyd et al., 2015). Nurturing talent is vital, and it is considered a social tragedy if gifted children do not have adequate support to develop their full potential (Gallagher and Gallagher, 1994). It is important to include visions, specific guidelines, and concepts on youth development directed to educating coaches, parents, and athletes altogether in order to achieve long-term success (McKeown and Ball, 2013).

In relation to the athletic talent development environment model (ATDE), this study is not related to athletes' levels (micro and macro) and domains (athletic and non-athletic) but to the personal environment and its impact on improvement. It is believed that successful athlete development needs such a personal and physical environment that supports athletes both at sport and personal levels (Henriksen and Stambulova, 2023).

Research proves that parents play a foremost and robust role in providing access to athletic activities early on, giving emotional support, and also supporting preparation and competition that lead to successes or failures (Alfeld-Liro et al., 1998). As their child progresses through the developmental stages, parents experience a shift in their role from exposing the child to different athletic opportunities towards becoming a facilitator and supporter (Côté, 1999).

Purpose of study

In relation to short track skating, it is suggested that the coaching program for young speed skaters incorporates active participation in other sports early on in their sport careers (Hillis and Holman, 2013). Technical development in early ages and also emphasis on development of basic movement skills enhances speed and optimal overall improvement. For a young skater, it is also crucial to plan age and development specific training that includes trainability, stamina, strength, speed, skill, and flexibility (Hillis and Holman, 2014).

Numerous studies identified the process of physical development during childhood and adolescence, and how they can impact short-term and long-term sports development and performance (Boisseau and Delamarche, 2000; Naughton et al.; 2000, Viru et al, 1999). It has been proved that the long-term preparation emphasizes the process of cooperation and preparation and not the "*win at all cost*" approach.

According to research, further evidence is needed on how to successfully adopt LTAD programs and practices (Nolte et al., 2017). Research describing the effectiveness of long-term athlete development has been also lacking (McKeown and Ball, 2013). There is need for more empirical research on sport talent identification and development altogether and on specific sport disciplines (Martindale et al., 2007), especially in speed skating (Hillis and Holman, 2014). Hence, the purpose of this study was to demonstrate how LTAD guidelines was adopted by the HNSF with specific focus on the official regulations, and coaches, athletes, and parents' perceptions.

MATERIALS AND METHODS

To seek convergence and validation (Bowen, 2009) of different data sources, and qualitative methods were used in the course of the research. First, document analyses were conducted to understand the main themes related to LTAD in Hungarian speed skating. Then, based upon the findings of the document analysis, questions were formulated to conduct the interviews.

Document analysis

The analysis included the following documents:

1. HNSF's Strategy,
2. HNSF's Operating Regulations,
3. HNSF's informative publication of Long-Term Athlete Development Program of Skating,
4. HNSF's educational publication of Long-Term Athlete Development Program for Speed Skating,
5. Educational materials of Sport Coaching MSc Program achieved in cooperation with the Hungarian University of Physical Education and Sports Science and the Hungarian National Skating Federation.

The documents were systematically reviewed, analysed, and assessed based on the following factors: 1) practical guidance for long-term planning and goals; 2) application of LTAD-model; 3) guidance for the successful implementation of coach-athlete-parent communication.

Selection of sample

Semi-structured interviews (N = 15) were carried out with five coaches (four males and one female), five speed skating competitors (three males and two females) from different levels, and one of the parents of each of the five competitors (N = 5, all females). The sample was selected through a simple, random sampling process, based upon the Hungarian National Skating Federation's list of certified coaches and list of competitors of those above 18 years of age.

The mean age of the interviewed coaches was 41.2 ± 5.2 years, on average they had been coaching for 13 ± 7.7 years. Four of the coaches have a university coaching degree and one of them has an intermediate coaching degree. All the coaches were formerly competitors on the Hungarian National Team.

The mean age of the competitors was 21 ± 2.45 years, on average they had been competing for 15 ± 1.87 years. Two competitors were members of the national team and placed 1-6 places at the World- and European Championship. Two competitors placed 1-5 at the National Championship and one competitor placed 1-5 at the National Junior Championship.

The mean age of the interviewed parents was 45.8 ± 5.91 years. One of them was the mother of a national team member skater, while four of them had children skating at the club level. It is important to note that the parents interviewed were not necessarily those of the competitors, as they were randomly selected.

Semi-structured Interviews

The interviews were conducted face-to-face and lasted 52-88-minutes (M = 72.2 ± 14) with coaches, 42-58 minutes (M = 52 ± 6.5) with competitors, and 35-43 minutes (M = 39.6 ± 3.2) with parents. It involved voice recording, note taking, and data recording. Numbers (1-5) and letters (A, C, P) were assigned to athletes, coaches, and parents.

The interviews' structure followed the same main guidelines as the document analysis. The interviews with coaches were separated into three main thematic sections focusing on: 1) the coaches' viewpoints on long- and short-term preparation; 2) their goals and certain elements of their training based upon the guidelines of LTAD; 3) the tasks of coaches in terms of creating emotional bonds between the competitors and discipline, and the experiences within the environment, as well as–following the guidelines of LTAD–the communication in the coach-athlete-parent triangle.

The interviews with athletes can be grouped into three main thematic sections as well: 1) mechanism of action on athletes regarding the coaches' views and practices and the goals of athletes; 2) affective effects on athletes through the coaches' long term planning and activity; 3) communication in the coach-athlete-parent triangle.

The three main thematic sections with parents were: 1) to what extent are they aware of the goals and guidelines of the preparation program applied by the coach; 2) how much information do they have on the preparation of their children and based on this, whether the coaches were following the LTAD method, and what are their expectations of preparation; 3) how effective is the communication between parents and coaches, and between parents and the federation.

Table 1. Research methods.

<table>
<tr><th colspan="5">Types of data collection</th></tr>
<tr><td>Document analysis (N = 5)</td><td colspan="4">Semi-structured interviews (N = 15)</td></tr>
<tr><td colspan="5">Points of view</td></tr>
<tr><td>- Practical guidance for long-term planning and goals
- Application of LTAD-model
- Guidance for the successful implementation of coach-athlete-parent communication</td><td colspan="4">-Fulfillment of long-term planning and goals
-Application of LTAD-model
-Fulfillment of coach-athlete-parent communication</td></tr>
<tr><td rowspan="4">1.HNSF's Strategy-2016.
2. HNSF's Operating Regulations-2016.
3. HNSF's informative publication of LTAD Program of Skating-2017.
4. HNSF's educational publication of LTAD Program for Speed Skating-2020.
5. Educational material of Sport Coaching MSc Program-2017 (Hungarian University of Sports Science & Hungarian National Skating Federation).</td><td>Participants</td><td>Gender</td><td>Mean age</td><td>Duration
(face-to-face)</td></tr>
<tr><td>Coaches
(N = 5)</td><td>4 male
1 female</td><td>41.2 yr
(SD = 5.2)</td><td>52-88 min.
(M = 72.2 SD = 14)</td></tr>
<tr><td>Athletes
(N = 5)</td><td>3 male
2 female</td><td>21 yr
(SD = 2.45)</td><td>42-58 min.
(M = 52 SD = 6.5)</td></tr>
<tr><td>Parents
(N = 5)</td><td>5 female</td><td>45.8 yr
(SD = 5.91)</td><td>35-43 min.
(M = 39.6 SD = 3.2)</td></tr>
</table>

Ethical approval was obtained (Institutional Review Board approval number: RK/680/2022). All interviewees gave permission for this study by signing the informed consent form on a voluntary basis.

Data analysis

The document analysis process combined qualitative content analysis and thematic analysis through which qualifying and quantifying data, coding, deliberating latent and manifest contents, and high-level interpretation was achieved. The systematic review of documentation provided sufficient background information in the pre-interview phase of the research. Similarities, differences, and general patterns were determined during the analytic procedure.

Data gathered from the interviews were summarized and compared question-by-question and finally thematic schemes were completed. The identified themes were compared based on the types of interviews then conclusions were drawn. Amid the analysis we followed Willis's content-based guidelines on detailed summaries of interview scripts (Willis, 2015). The coding approach included systematic coding and recoding.

RESULTS

According to the documents

Long-term planning and goals

All the documents have direct content and definitions on long-term planning. In the HNSF's Strategy long-term plans and tasks are indicated by a timeline containing general goals and tasks, facility development, selection, competitive and professional sport, talent care, education, social inclusion, communication, and sports diplomacy (Table 2). This is the only document in which LTAD model is not mentioned directly, while every other document highlights the most important criteria of LTAD as an example to follow in planning and training. The HNSF's Operating Regulations, the informative publication of LTAD Program of Skating, the educational publication of LTAD Program for Speed Skating, and the educational material of Sport Coaching MSc Program all describe the LTAD model in relation to long-term planning and goals.

Table 2. Formulated strategic subtasks outlined in the federations' strategy.

Strategic subtasks	Description of subtasks
General goals, tasks	Includes the construction of the organization and the full provision of personnel conditions, as well as the creation of a corporation under the association and its economically successful operation. Emphasizes the need for increasing the number of member organizations and operating an Academic System.
Facility development	Includes the construction of the National Olympic Skating Center, also of 3-4 ice rinks for exclusive use in the regional centers.
Selection	Recruitment, wide youth base, reconsidered selection program and competitive system appear as long-term tasks. Involving kindergartens and schools in talent search programs.
Competitive and professional sport	The modernization of competition systems, the employment of foreign specialists and an increase in the number of competition license holders were set as requirements.
Talent care	Reducing attrition, ensuring interoperability between sports, running recruitment development programs and competition systems, high-level operation of selected squads, operation of dual career programs, joining the talent management programs of the Hungarian Olympic Committee are highlighted.
Education, post-graduation	Close cooperation with universities for education of sports professionals and to ensure dual carriers.
Social inclusion	Supporting the sports of disabled, minorities, those at risk or in other disadvantaged situations are expected.
Communication	Communication with sponsors, supporters, public media, fans, and member organizations is detailed.
Sport diplomacy	Strengthening sports diplomacy in the International Skating Union, initiating the formation of the European Skating Union is emphasized.

Application of the LTAD Model

As presented earlier, besides the HNSF's Strategy, all other documents give certain information on the topic. Documents give a general and easy to follow guidance of the LTAD model. LTAD in these documents is phrased as a philosophy that drives change, and is a means of paradigm shift, which helps an athlete-centred development framework to become generally accepted in Hungarian speed skating.

> *"It is a development path that is understandable for everyone, starting from playgrounds all the way to racetracks or ice-rinks withstands full of spectators." (HNSF's informative publication of LTAD Program of Skating, p.20)*

The documents go into detail of the tasks according to ages, mentioning such subtasks as transfer of information, communication and cooperation, and it also provides guidance for planning and approach in terms of sport pedagogy and ethics.

> *"The central task is to provide a program suitable for the development of early, average or late-maturing skaters in terms of optimal training, competition and regeneration. The harmful effects of early sports specialization are well-documented in the international literature." (Educational material of Sport Coaching MSc Program, p.15)*
>
> *"The long-term approach to an athlete's development is holistic. It takes into account not only the performance on ice, but also the physical, social, mental development of the participants. (HNSF's publication of LTAD Program for Speed Skating, p.24)*
>
> *"The program promotes harmony, communication and the flow of information between the Federation, member organizations and clubs. The program covers the teaching of parents of the process of short- and long-term preparation, during which it contributes both theoretically and practically to the development of children to ensure nutrition, regeneration and a lifestyle appropriate for their age." (HNSF's educational publication of LTAD Program for Speed Skating, p.4)*

Based on the official documents, all participants of the community have a tangible support for understanding and applying LTAD. The federation has made all documents available for everyone.

Multi-sided communication

Similar to earlier topics, with the exception of the HNSF's Strategy, every document places importance on communication in the 'sports triangle' and the need to introduce the LTAD to every participant in the system. The informative publication of LTAD Program of Skating states that there are gaps in sports, like educating parents on long-term development, which in fact the LTAD provides solutions.

> *"Parents and coaches have to cooperate for the success of the competitor and not in the least for their mental health." (HNSF's educational publication of LTAD Program for Speed Skating, p.13)*
>
> *"Monitoring the living conditions of athletes is justified." (HNSF's Operating Regulations, p.9)*

The educational publication of LTAD Program for Speed Skating also includes schools in the communication structure. However, the HNSF's Strategy does not include any of this communication structure instead it explicitly limits references to communication to press, sponsors, and supporters. Furthermore, the Federation has a goal to extend communication towards member organizations, audience and fans.

View of the participants

Long-term planning and goals

The coaches were aware of and applied the long-term preparation method. They emphasized the need of balance between success and long-term planning. Moreover, the education of conscious athletes was also among their goals.

> *"I clearly apply the long-term preparation. The federation supports the long-term preparation." C1*
>
> *"I believe in the long-term preparation. The work done will have its results." C3*
>
> *"We prepare in accordance with the long-term preparation. Preparation is more important to me than chasing immediate results. I resist the pressure of parents and through constant education I try to teach them to apply long-term thinking. The federation also expects this direction." C2*

The interviews with athletes accurately reflect the views of coaches on long-term preparation, as the athletes stated that preparation for them is considered as important as success at competitions. They mentioned that difficulties of preparation are easily processed with the help of their coach.

> *"You cannot always win in the long run, but with the coach you can learn from every competition." A3*
>
> *"We have to try to win, whenever possible. After all, we have to be flawless in the most important moment. This differentiates the Olympic Champion from the rest." A1*
>
> *"In the long run, I prepare for the Olympics, it's enough to win that (laughter)." A4*
>
> *"Everyone makes mistakes. What's important is not to make mistakes at my most important competition." A5*

Three national team athletes set long-term goals of qualifying for Olympics. Only one competitor has a short-term goal and explained that she loves what she does and wants to win all the competitions now, since anything can happen in the future.

> *"I love what I'm doing, I would like to win at every competition if it's possible. I don't think forward, I always try to perform well at the upcoming competition. I don't think it's good to set long-term goals because anything can happen." A4*

In the case of parents, the lack of understanding about long-term preparation goals and LTAD model was clearly present.

> *"I've heard about the program, maybe the coach talked about it. It's about the long-term preparation of the competitors, but I don't have further information on it." P3*
>
> *"I haven't heard of it, but I guess it's about the preparation of competitors." P1*
>
> *"I don't know what our preparation was based on. I haven't heard about the program." P5*

Application of LTAD Model

All the interviewed coaches are well prepared on the LTAD model and its functions, and they claim that they apply it in their daily work. They follow its suggestions on the affective scope of preparation, as the need for excessive results (winning competitions) can destroy dedication to the sport; for example, the realization of a technical or tactical element by the athlete needs to be highlighted as a result. Their primary goal is to develop an attachment of young competitors to the sport through playful and experience-based exercises. Another goal is for competitors to be on the national team so that they can gain the appropriate experiential and motivating skill development.

The affective effects of LTAD on athletes are shown by the description of their feelings: sport makes them happy, strengthens them mentally, and prepares for life. They enjoy improving their skills and, at the same time, they are involved in participating in sports other than their own, which they believe allows for complex development.

While the coaches clearly know and apply the LTAD program and the competitors advocate the developmental approach of the program, the parental opinions are different. Some of them approach the sport exclusively from the side of performance, while others highlight the educational value of it. Parents do not know if coaches apply LTAD because they do not have enough information about the model. Out of the interviews made with parents, only two declared that the short-term and long-term goals are of equal importance.

> *"In order to keep developing they must reach better and better results. Their opponents don't rest either, the pressure is continuous." P1*

> *"Everybody wants to win, staying in the national team and going forward demands us to win at every competition." P5*
> *"Sport is about performance. The goal is to succeed at the worldwide competition; the main goal is the Olympics. The possibility of unsuccessfulness, of not performing well at a competition, always makes us learn. Sports are beautiful because in their case accomplishment doesn't need to be explained." P2*

It was not important for the rest of the parents to have their child win at every competition because they concentrate on the long-term goals.

> *"It's not a problem if they don't win at every competition, as we prepare for the Olympics. Until then, they will lose many times at competitions, but they will learn and gain experience from that. As an Olympic Champion, they won't even remember they lost these competitions." P3*

Multi-sided communication

In the opinion of coaches, establishing a supportive environment and a close parental partnership is a major condition for effective work. It can be stated that coaches are satisfied with the communication between them, the athletes and the parents. Moreover, they emphasized the need for keeping a distance, as some parents try to cross boundaries. Similarly, the competitors shared positive experiences regarding the coaches' communication; according to their experiences the coaches regularly talk to their parents. The parents' opinions, however, were diverse due to the coaches' inappropriately defined goals and the lack of deep conversations.

> *"If the coach told me what their goals are with my child, I could support that process at home." P5*

DISCUSSION

There has been little scientific attention on the impact of applying LTAD in speed skating (Telegdi, 2020). Our former analysis on the LTAD function pointed out that applying the program was not successful in every area, thus further development in this sport was not guaranteed. It was concluded in that study, that coaches were mostly working based upon a short-term preparation system. This was due to pressure to achieve results, which came from their own misconception and expectations from parents. Moreover, coaches emphasized the lack of parents' involvement and well-working communication.

The findings of this research demonstrated that the absences found in our earlier research have begun to decrease. Most of the coaches' work based on the principles of long-term preparation, which is also reflected by the views of competitors.

In the course of our document analysis, we came to the conclusion that most of the Federation's documents and publications are written in accordance with the principles and guidelines of LTAD. Part of these are easily accessible through the website of the Federation. There are still deficiencies in communication that can especially be seen in the coach-parent relationship. Moreover, it was observed that the parents' knowledge of LTAD was lacking.

The education of parents, knowledge of the principles of LTAD, and continuous communication assists the effectiveness of the coaches' work, as parents can help the efficiency of the LTAD program by providing support outside of trainings. In Hungarian speed skating the deficient communication and education obstruct the optimal and effective operation of the program, due to the lack of support from the side of the parents. Communication with parents as a strategic element in the strategy of the federation seems justified, which we regard as an effective way to terminate deficiencies.

Our results support earlier study (Dorsch et al. 2021) in stating that sport-parenting programs are clearly needed in youth sport and educating parents can result in parents helping their children fulfil their athletic and human potential. According to recent findings (Trudeau et al., 2021), coaches are more likely to adopt LTAD concepts into their practices, if they have sufficient understanding of LTAD, they have a coaching certification, and a perceived organizational support. However, coaches interviewed by Beaudoin et al. (2015) believed that short-term financing was still predominant and this was the main barrier to implementing LTAD in their respective sport. It is imperative to understand that parent involvement is multidimensional and thoughts, emotions, and family sources (i.e., money, time) related to the child's sport activity define parents' behaviour in terms of support and pressure (Dorsch et al., 2018). It is suggested that HNSF work out a complete parent-education program for appropriate parental involvement.

Burke et al. (2021) examined the efficacy of several parent-education programs across a range of sport disciplines and concluded that developing longitudinal programs should be continued to facilitate extended parental involvement and interaction. The parental involvement model proposed by Hellstedt (1987) describes overinvolved, under involved and moderately involved types of parents. From this an educational program should be built up systematically, emphasizing all positive and negative consequences of parental behaviours that guides and teaches parents through specific counselling for optimal involvement (Sacks et al., 2008).

Our research proves that parents need education on the LTAD model in order to better understand its aims, stages, expectations, and preparation required. This solution is in the hand of sport leaders. Our conclusion is that application of LTAD in Hungarian speed skating is promising and moving in the right direction, which can be seen in the results of the athletes. Thorough communication with all parties requires change on the part of the Federation in order to create the optimal environmental conditions for athletes' development.

AUTHOR CONTRIBUTIONS

Attila Telegdi, Gabriella Trzaskoma-Bicsérdy and József Bognár conceived and designed the investigation, analysed and interpreted the data, drafted the manuscript, and approved the final version submitted. Attila Telegdi collected data.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DECLARATION

The experiment complies with the current law of Hungary. Ethical approval was obtained (Institutional Review Board approval number: RK/680/2022).

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ORIGINAL ARTICLE

Differences between male and female referees in adjudicating male soccer matches

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ABSTRACT

Referees play important roles in the soccer matches, i.e., adjudicating the outcome of the soccer match and the players' performance. Female referees were included into male soccer matches and received a lot of attention recently. Although female referees were suggested to be less competent than male referees and also suffered from discrimination, few studies have not directly compared the female and male referees in adjudicating the male soccer matches. In this study, the data from the last five seasons of Maurice Revello Tournament Cup matches were compared to see whether referee gender differences were exited in adjudicating the players' performance in the tournament. The hypothesize is there were no difference between different genders referees in adjudicating matches. Data from 109 matches (52 with female referee and 57 with male referee) from the 2018 to 2024 seasons were selected and divided them into two groups based on different referee genders. All variables (scores, shots, shots on target, passes, fouls, penalties, yellow cards, red cards, offsides, and corners) were analysed using independent samples t-tests and generalized linear models. The results showed there were no significant difference in all variables (scores, p = .94, shots p = .076, passes p = .729, fouls p = .541, offsides p = .249) between matches adjudicated by female and male referees. The findings indicated that female referees were not weaker than male referees in adjudicating the male soccer matches. It can break the gender prejudges bias and discrimination against female referees and encourage more women to join as soccer referee and adjudicate in male soccer matches.

Keywords: Soccer referees, Female, Matches performance.

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INTRODUCTION

Soccer referees were important roles which decisions inevitably have an impact on the outcome of the matches (Weston, M. et al., 2011, Vasilica, I et al., 2022). They need to make quick and accurate decisions during the match, considering various sources of information (Spitz, J. et al., 2021). Study reported that a referee was required to do over 130 observable decisions during a professional soccer match (Helsen, W. et al., 2006). Referees' decision-making capacities were influenced by various external matches' factors, such as crowd noise (Balmer, N. et al., 2007) , match location (Boyko, R. et al., 2007), social forces (Zelyurt, M. K., & Ataçocugu, M. S., 2017) within-matches pressure from players and coaches (Kubayi, A. et al., 2022), as well as the previous decisions in the matches (Plessner, H., & Betsch, T., 2001). The accuracy of the referee's decisions would affect the outcomes of the matches (Fontenla, M., & Izón, G. M., 2018). Prior studies have demonstrated that the accuracy of referee decision was affected by a number of factors, such as position and distance (Mallo, J. et al., 2012), angle of view (Mallo, J. et al., 2012), match period (Samuel, R. D. et al., 2021), experience level (Nurcahya, Y. et al., 2021), matches control (Jin, G. et al., 2022), physical fitness (Krustrup, P. et al., 2009) and bias (Lane, A. M. et al., 2006). These have given rise to a deepening interest in examining the factors that condition the referee's decision during matches. The decisions of referee would have an impact on a player's matches performance. Study showed the standards of foul decision affected the intensity of player opposition and variations in the referee's decision standards would affect the performance of players throughout the period of the match resulting in variations in the intensity of the matches or the adventurous of the matches (Fontenla, M., & Izón, G. M., 2018). Red and yellow card decisions might make players more cautious in their follow-through and less effective in the matches (Badiella, L. et al., 2023). In addition, referee's movement routine and methods during the matches could affect team matches tactics and player movement options (Jiang, J. et al., 2023). Finally, the unfair decisions which players think had a negative impact on their morale, confidence and performance (Lex, H. et al., 2015).

Previously female referees mainly adjudicated female soccer matches. Match analysis study had shown that male soccer matches were played at a faster pace than female soccer matches (Krustrup, P. et al., 2005). Specifically, in tournaments at comparable levels of competition, female professional players moved only two-thirds of the distance of male players at high intensity (i.e., speeds ≥15 km-h-1) (Datson, N. et al., 2014). This demonstrated that male soccer players were actually subjected to greater external loads. Study also showed there were fewer fouls in female soccer matches than in male matches, and male soccer matches were more passing accuracy and more confrontational (Pappalardo, L. et al., 2021). Compared to male referees, female referees physical fitness were weaker than male referee (Castagna, C. et al., 2018). Female matches had less requirements in matches management and foul recognition (Pappalardo, L. et al., 2021). Female referees were exposed to sexist language and abuse when adjudicating matches, sometimes related to traditional gender roles or the incompetence of female referees, and sometimes in the form of extreme and threatening behaviour (Gubby, L., & Martin, S., 2024). There were also some bias against female referees, as studies had shown that female referees were incompetent, weak, unqualified and unskilled (Perreau-Niel, A., & Erard, C., 2015). They were also more vulnerable to violence and discrimination and faced a wider range of gendered barriers than men (Reid, K., & Dallaire, C., 2020).

Although a large number of studies have expressed the view that female referees were inferior to male referees (Pappalardo, L. et al., 2021; Castagna, C. et al., 2018). However, there was also evidence proved that top female referees could achieve the physical demands of medium-standard male referees and maintained the distance from the ball throughout the matches (Mallo, J. et al., 2010). Meanwhile, female referees' weaknesses in aerobic endurance are not associated to the decision making abilities (Castagna, C. et al., 2018). The combination of gender and technology and how they affect refereeing roles has not been the focus of research (Skirbekk, S., 2024). In recent years, female referees have increasingly appeared in male soccer matches. However, to the best of our knowledge, no study has been conducted to directly compare whether there are difference between male and female soccer referees on the performance of players in male soccer matches.

This study aimed to compare the performance between male and female referees in adjudicating male soccer matches in different seasons of the competition, using the Maurice Revello Tournament Cup as an example. We hypothesize that there were no difference between male and female referees in adjudicating goals, shots, passes, fouls, penalties, yellow cards, red cards, offsides and corners in matches.

METHODS

Match sample

The sample included total of 109 matches played in the Maurice Revello Tournament Cup (52 with female referee and 57 with male referee) from the 2018 to 2024 seasons. Female referees were first entered to the Cup in 2022 season. Therefore, the seasons pre and post the entrance of female referees were compared and analysed. All the data were obtained from the official website of the Maurice Revello Tournament Cup (www.tournoimauricerevello.com) and Google (www.google.com). Match data for the 2024 Maurice Revello Tournament Cup were taken from the post-match reports on its official website. Other seasons match data were taken from the post-match reports on Google (search key words ‘Maurice Revello Tournament Cup’) page. Match data were provided by the company’s observational system (OPTA Client System). The OPTA client system is used to collect real-time football match statistics, with operators manually entering match events and statistics in real-time; the system is predefined to cover every touch and touch action that may occur during a match; comprehensive event tracking (including player-specific actions) is available; and to ensure accuracy, the same match can be independently coded by multiple operators for cross-checking and validation (Liu, H. et al., 2013). The interoperate reliability of the OPTA used to collect soccer match statistics was identified as reliable reaching an acceptable level of Kappa, ICC, r and SEM values. The data set will be double-checked to improve the accuracy of the data. Furthermore, the data is publicly available and free of charge. This Ethics of the research was approved by Hong Kong Baptist University.

Selection of match performance metrics

In accordance with similar studies, the selection of match performance metrics should be included players’ self-players, opponent performance and the decision-making of the referee (Bao, R., & Han, B., 2024). Therefore, the indicators included: scores, shots, shots on target, passes, fouls, penalties, yellow cards, red cards, offsides, and corners (Fernández-Cortés, J. et al., 2022). In addition, some other data (e.g. 1st half time, 2nd half time and total time) can be used to explore the impact of different sex of referee. However, since such data was generally not publicly available, it is difficult to obtain. Therefore, this study preferred to analyse the accessible data from the Maurice Revello Tournament Cup website.

Data analysis

All data were presented as means ± SD and imported into SPSS (version 29.0, Illinois, USA) for analysis. The statistical significance was set to $p < .05$. Firstly, an independent sample T-test was used to compare the performance metrics between female referees and male referees. In addition, a generalized linear model (GLM) was initially fitted for each variable with using the Bayesian Information Criterion (BIC) and 95% confidence intervals (CI). Effect sizes (Cohens ’d) were categorized as small (d = 0.20), medium (d = 0.50) and large (d = 0.80).

RESULTS

Table 1 presented the descriptive statistics and the comparison of match performance variables for the Maurice Revello Tournament Cup between female and male referees. There were no significant different in all variables. Female referees adjudicating matches had more shots than male referees' matches (*p* = .072, Cohens' d = 0.349, 95%CI (−0.031, 0.727) approaching significant level. For other variables, there were not significantly more in score, shots on target, passes, yellow cards, red cards, offsides, and corners than male referee's matches. Meanwhile, male referee matches in fouls and penalties not significantly more than female referees.

Table 1. Changes of indicators between female and male referees.

Variables	**Female**		**Male**		**t**	***p***	**Cohen's d**	**95% CI for Cohen's d**	
	Mean	SD	Mean	SD				Lower	Upper
Scores	2.69	1.89	2.67	1.64	0.076	.940	0.015	-0.361	0.390
Shots	22.17	5.66	20.23	5.50	1.818	.072	0.349	-0.031	0.727
Shots on target	8.04	2.58	7.65	3.02	0.780	.473	0.138	-0.239	0.504
Passes	792.02	115.68	784.54	108.60	0.348	.729	0.067	-0.309	0.443
Fouls	27.10	6.47	27.82	5.93	-0.613	.541	-0.118	-0.494	0.259
Penalties	0.25	0.52	0.33	0.55	-0.815	.417	-0.156	-0.532	0.221
Yellow cards	3.98	1.90	3.68	2.35	0.719	.474	0.138	-0.239	0.514
Red cards	0.17	0.43	0.14	0.35	0.437	.663	0.084	-0.292	0.460
Offsides	3.92	2.09	3.46	2.11	1.160	.249	0.222	-0.155	0.599
Corners	8.04	2.58	7.65	3.02	0.720	.403	0.161	-0.216	0.537

Table 2 showed the estimated findings of the Generalized Linear Model for every matched performance variable. The results also showed that there were no significant different in all variables between the different gender of referees. Same as Table 1. shots variable was also near to significant levels (*p* = .066). Compared with effect size of the t-test in Table 1, all variables were in small effect size and the results of the generalize linear model show that the p-values of all variables were not at significant levels, consistent with independent t test statistics results.

Table 2. Estimation results of the generalized linear model (GLM).

Variables	**Estimate**	**SE**	**95% CI**		***p***
			Lower	Upper	
Scores	0.026	0.336	-0.630	0.681	.939
Shots	1.945	1.060	-0.132	4.022	.066
Shots on target	0.389	0.536	-0.661	1.439	.467
Passes	7.475	21.286	-34.245	49.145	.725
Fouls	-0.728	1.177	-3.034	1.578	.536
Penalties	-0.083	0.101	-0.282	0.115	.411
Yellow cards	0.297	0.409	-0.505	1.098	.468
Red cards	0.033	0.742	-0.113	0.178	.659
Offsides	0.467	0.399	-0.315	1.249	.242
Corners	0.495	0.584	-0.650	1.640	.397

DISCUSSION

This research revealed finding that there were no difference in all variables between female and male referees. The effect size were very low that indicated that different gender referees had a limited impact on match performance and did not directly affect these match variables. This could prove that the difference between female referees and male referees did not have a significant impact on players' matches performance.

In recent years, there are more and more female referees appearing in male matches, including the World Cup in Qatar, UEFA Champions League, Asian Cup and many male professional leagues in various countries. However, as far as the researcher's survey is informed, there was a lack of research comparing female soccer referees and male referees adjudicating matches on player performance. Therefore, this study provided a valuable analysis of the comparison of female and male referees on the same tournament (Maurice Revello Tournament Cup).

Checking the distance between the referee and the ball during the matches seemed to be crucial as an parameter to objectively assess the physical and technical performance of the referee, representing the referee's ability to follow the matches (Mallo, J. et al., 2009). Based on the findings of this study we found that there was no significant difference between the adjudicated performance and ability of female and male referees. Previous studies have shown that top female soccer referees can achieve the same level of fitness as male referees. At the same time, they could keep their distance from the soccer during the periods of the matches (Mallo, J. et al., 2010). Similarly, another study of top female assistant referees revealed that, in addition to high intensity activity levels, the athletic demanded of top female assistant referees were similar to those of top male assistant referees as well as the ability of the assistant referees to maintain their distance from the offside line during the matches, suggesting that they were able to keep up with the pace of the matches (Mallo J. et al., 2010). So these studies can be assumed that there was no difference in the physical activity and technical ability of male and female referees when they are adjudicating matches and that it would not have any impact on match performance.

A previous study suggested that there was a huge difference in aerobic capacity between male and female referees, with female referees significantly weaker than male referees, mainly in maximal oxygen consumption (VO_{2max}) (Castagna, C. et al., 2018). However, the fitness performance of soccer referees may be related to variables other than VO_{2max} (Castagna, C. et al., 2007). Although female referees were weaker than male referees in terms of aerobic ability, there was no research to suggest that minimum levels of aerobic capacity were of practical significance for experienced referees to cope with the demands of the matches (Castagna, C. et al., 2018). According to FIFA regulations, in order to ensure that female referees were physically fit to adjudicate male football matches, all female referees should pass the male physical fitness-test before entering men's matches. Although it has also been argued that physical fitness test standards do not have high structural assessment validity for referee fitness evaluation (Weston, M. et al., 2009), selected female referees would not be significantly weaker than male referees in terms of physical fitness.

The type of matches also had an impact on the ability of the referee. Male players ran longer total distances had higher speed thresholds, had higher passing accuracy and were more dominant in the second half during the matches (Bradley, P. S. et al., 2014). On the contrary, female athletes were less muscular and their style of play is less aggressive (Althoff, K. et al., 2010). Differences in the pace and intensity of the matches can make it difficult for female referees to adapt and lack of experience in adjudicating male soccer matches. This created some challenges for female referees in terms of matches management.

In addition, a large number of previous studies have revealed society's bias against female referees. A study on referee gender and bias revealed that biases against women were powerful regardless of the referees' level of expertise and that male referees' stereotype toward female players tends to be negative, particularly in terms of decision-making (Souchon, N. et al., 2013). Some female referees were capable of competently refereeing soccer matches but still be marginalized in referee department (Reid, K., & Dallaire, C., 2019). Female referees were more likely to be subjected to sexism and harassment during matches (Drury, S. et al., 2022). While it was more acceptable for women to "*present*" their soccer identity in traditional ways, they were also condemned for failing to appropriately display normative femininity or criticized for "*behaving like men*" (Forbes, A. et al., 2015). This could lead to persecution of female referees, often in the form of sexist and homophobic abuse (Jones, C., & Edwards, L. L., 2013).

It was often assumed that female lack the knowledge needed to make good decisions, that they failed to embody the assertive character needed to control the matches, and that they did not have the physical ability to "*keep up*" with the matches, especially in the elite men's matches. But these assumptions were largely rooted in unfounded claims of biological determinism and gender differences circulating in the soccer industry (Reid, K., & Dallaire, C., 2019). The lack of real and reliable matches and data analyses make it difficult to break the bias against female referees.

Another finding was that the matches adjudicated by female referees had more shots compared with male referees according to the result. These factors were related to team tactics and style of play, with teams employing more attacking or possession strategies tending to shoot and score more goals than defensive teams (Dwyer, D. B., & Young, C. M., 2024). This may reflect the fact that matches officiated by female referees are more conducive to the development of attacking skills and tactics.

This study directly observed the influence of female and male referees on athletes' performance by comparing differences in matches data. The objective and factual data is one strength of the present study. Nonetheless, there are some limitations in this study. First, the number of match cases were small and too few data variables. Second, the case for the tournament spanned a long period of time, and some of the laws of the matches and the technical and tactical have changed somewhat dramatically, especially some years affected by Covid-19. Last, the team varies from different seasons and other variables such as team strength were not taken into account.

In future study designs, the first is to increase the match sample size, and the variables of data that can be used to. Second, other relevant variables should also be considered, such as league or cup competitions (end of season matches may be more important than early season matches, and knockout matches are more important), the referee's own style of play, and team strength variables. If possible, other physiological indicators such as heart rate, Rate of perceived exertion (RPE), lactate, and so on can be collected from players and referees to assess their performance.

CONCLUSION

This study observed the effect of different genders of referees on players' sport performance in Maurice Revello Tournament Cup. The results of the current study indicated that female and male referees adjudication male matches were have no different effect on players' performance.

This study could serve as a pilot study for future research on gender in soccer referee. At the same time, it can break the gender prejudges bias and discrimination against female referees and encourage more women to join as soccer referee and adjudicate in men's soccer matches.

AUTHOR CONTRIBUTIONS

Yuxin Zuo, Xuan Liu, Fenghua Sun, Yizhou Yang and Yao Tong were involved in study design, data collection and management. Yuxin Zuo, and Xuan Liu wrote this manuscript. Yuxin Zuo and Xuan Liu contributed equally to this work. All authors read and approved this manuscript before publication.

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No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Validation of the sexual prejudice in sport scale in Brazil and Portugal

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ABSTRACT

This study examines sexual prejudice in sport within Brazilian and Portuguese contexts, cross-culturally validating the Scale of Sexual Prejudice in Sport (SPSS). The study included 618 university student-athletes (348 Brazilian; 270 Portuguese). Confirmatory factor analysis corroborated the three-factor structure of the instrument in both countries, with adequate fit indices. Male athletes demonstrated greater sexual prejudice in both countries ($p < .05$), reinforcing the heteronormative nature of the sporting environment. Right-wing political orientation emerged as a significant predictor of negative attitudes in both samples, while religiosity proved significant only in Portugal ($\beta = .185$, $p < .01$). Important differences were observed regarding political interest: in Brazil, greater interest was associated with elevated levels of prejudice ($\varepsilon^2 = .033$, $p < .01$), contrasting with Portugal. Hierarchical regressions revealed that attitudes toward lesbians and gays constituted the strongest predictor of sexual prejudice in both Brazil ($\beta = -.475$, $p < .001$) and Portugal ($\beta = -.256$, $p < .001$). The results contribute to the understanding of sexual prejudice in sport in Portuguese-speaking countries and suggest the need for specific interventions considering the sociocultural particularities of each context.

Keywords: Sexual prejudice, University sport, Cross-Cultural studies, Gender attitudes, Scale validation.

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INTRODUCTION

Sexual prejudice refers to collectively negative attitudes and stereotypes directed toward individuals who identify as or are presumed to be lesbian, gay, bisexual, or transgender (LGBT), as their behaviour is perceived as unnatural (Herek and Capitanio, 1996) and immoral (Sartore and Cunningham, 2009). Studies demonstrate that maintaining traditional gender role beliefs is associated with a greater tendency to develop negative attitudes toward those who do not conform to traditional gender expectations and, consequently, to express sexual prejudice (Cunningham and Melton, 2013; Lee and Cunningham, 2016; Mullin et al., 2024).

The sporting environment is described as inherently heterosexist and structured to defend the principles of hegemonic heteronormative masculinity (Sartore-Baldwin, 2013; Denison et al., 2020; Knoester and Allison, 2021). Heteronormativity refers to a culturally shaped view that presumes heterosexuality as the normal and natural standard, based on essentialist biological notions about the distinct and complementary roles of males and females (Butler, 2016). LGBTQ+ athletes face constant pressure to conform to these traditional gender roles and sexual orientation expectations, resulting in documented negative consequences such as distress, social withdrawal, mental health problems, and low self-esteem (Scandurra et al., 2019; Symons et al., 2017).

Research examining LGBTQ+ individuals in sports has expanded but remains concentrated in countries such as the United States and the United Kingdom. Portuguese-speaking countries lack validated instruments to measure sexual prejudice in sporting contexts (Oliveira et al., 2013; Piedra et al., 2017). The Sexual Prejudice in Sport Scale (SPSS) provides a comprehensive and contemporary psychometric measure of negative attitudes toward sexual minorities in sporting environments (Baiocco et al., 2020). This study aims to translate and cross-culturally validate the SPSS for use in Portuguese, as well as apply it to university student-athletes to measure levels of sexual prejudice in this population.

MATERIALS AND METHODS

Participants

This study included 618 higher education students, of whom 348 were Brazilian and 270 were Portuguese. The mean age of Brazilian participants was 25 years (*SD* = 7.0) and Portuguese participants was 23 years (*SD* = 5.0). The distribution of sports modalities presented marked differences between Brazil and Portugal. In Portugal, track and field stood out as the most practiced modality (n = 113; 41.9%), followed by karate (n = 45; 16.7%), soccer (n = 40; 14.8%), volleyball (n = 28; 10.4%), and tennis (n = 16; 5.9%). In Brazil, a distinct distribution was observed, with handball showing the highest participation (n = 87; 25.0%), followed by indoor soccer (n = 65; 18.7%), volleyball (n = 58; 16.7%), basketball (n = 42; 12.1%), and a tie between soccer and running (both with n = 18; 5.2%).

Table 1 presents the complete sociodemographic characteristics of the sample.

Instruments

Sociodemographic Questionnaire: Gathered participant information including age, gender, ethnicity, sexual orientation, level of political interest, general political views, religion, and religious importance.

Sexual Prejudice in Sport Scale (SPSS): The SPSS (Baiocco et al., 2020) consists of 19 items measuring attitudes toward gays and lesbians in sporting contexts using a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree), with higher scores indicating more negative attitudes. Baiocco et al. (2020) established the factorial structure of the scale through two Italian studies: an initial study with 297 heterosexual athletes, followed by reliability and validity tests with 311 heterosexual athletes and 160 gay or lesbian athletes. Exploratory factor analysis revealed three subscales – open rejection, denial of visibility, and gender performance – that explain 62.73% of the variance. The instrument demonstrated strong internal consistency, with α = .71 to .93 for heterosexual participants and α = .77 to .90 for LGBT participants across subscales and total scores. Test-retest reliability coefficients indicated adequate temporal stability: r = .92 (total score), r = .91 (open rejection), r = .71 (denial of visibility), and r = .88 (gender performance).

Table 1. Sociodemographic characteristics (N = 638).

Variable/Category	Brazil (n = 348)	Portugal (n = 270)
Gender		
Female	211 (60.63)	112 (41.48)
Male	137 (39.37)	158 (58.52)
Sexual orientation		
Heterosexual	233 (66.95)	155 (57.41)
Bisexual	60 (17.24)	94 (34.81)
Homosexual	55 (15.80)	10 (3.70)
Other/Pansexual	0 (0.00)	11 (4.07)
Ethnicity		
White	237 (68.10)	224 (82.96)
Black/African	72 (20.69)	22 (8.15)
Hispanic/Latino	39 (11.21)	21 (7.78)
Mixed/Romani	0 (0.00)	3 (1.11)
Socioeconomic status		
Very low/Low	72 (20.69)	39 (14.44)
Middle	259 (74.43)	217 (80.37)
High/Very high	17 (4.89)	14 (5.19)
Religion		
None	131 (37.64)	116 (42.96)
Christian/Catholic	166 (47.70)	130 (48.15)
Evangelical	20 (5.75)	16 (5.93)
Spiritist	23 (6.61)	4 (1.48)
Others	8 (2.30)	4 (1.48)
Level of religiosity		
Not religious	75 (21.55)	47 (17.54)
Moderate	209 (60.06)	201 (75.00)
Very religious	64 (18.39)	20 (7.46)
Political positioning		
Left	184 (52.87)	235 (87.04)
Centre	143 (41.09)	32 (11.85)
Right	21 (6.03)	3 (1.11)
Political interest		
None	20 (5.75)	122 (45.19)
Little	141 (40.52)	130 (48.15)
Moderate	134 (38.51)	12 (4.44)
High	53 (15.23)	6 (2.22)

Multidimensional Scale of Attitudes Toward Lesbians and Gays (Escala Multidimensional de Atitudes em Relação a Lésbicas e Gays- EMAFLG): Developed and validated in Portugal by Gato et al. (2012), the MSALG contains 27 items rated on a 6-point Likert scale (1 = strongly disagree, 6 = strongly agree). The instrument includes three negative subscales: Homopathologization (5 items), which assesses pathologization and moral judgments about homosexuality; Rejection of proximity (10 items), which measures avoidance and discomfort with lesbians and gays; and Modern heterosexism (7 items), which examines contemporary prejudices regarding conjugality and parenthood. A positive subscale, Support (5 items), evaluates attitudes toward advocating for lesbian and gay rights. The scale demonstrates adequate internal consistency (total scale α = .87; subscales α = .79 to .91).

Data analysis

The construct validity of the SPSS was investigated through confirmatory factor analysis (CFA) using structural equation modelling (SEM). Several fit indices were evaluated: chi-square/degrees of freedom ratio (χ^2/df), standardized root mean square residual (SRMR), goodness of fit index (GFI), comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and 90% confidence interval for RMSEA. The criteria suggested by Xia and Yang (2019) for good fit were considered: χ^2/df ≤ 5; SRMR ≤ .08; GFI, CFI, TLI ≥ .90; RMSEA ≤ .08, with the 90% confidence interval of RMSEA containing 0.

Discriminant validity was assessed using Fornell-Larcker criteria and heterotrait-monotrait ratio (HTMT ≤ 0.85) (Henseler et al., 2015). Additional evidence was obtained through cross-loading analysis, examining standardized factor loadings (≥ 0.50) and average variance extracted (AVE ≥ 0.50) (Hair et al., 2019). Internal consistency was verified by Cronbach's alpha coefficients (≥ 0.70) and composite reliability (≥ 0.60).

Spearman correlations between SPSS scores and MSALG results were used to evaluate convergent validity, in addition to descriptive statistics. Parameter stability was verified by bootstrapping with 5,000 resamples. Levels of sexual prejudice in demographic groups were examined by non-parametric Mann-Whitney U and Kruskal-Wallis tests (Rani Das, 2016). Associations between sexual prejudice in sport and demographic variables were analysed by Spearman correlations. A hierarchical multiple regression was performed to analyse the predictive effects of demographic variables and attitudes toward gays and lesbians on sexual prejudice in sport.

RESULTS

Psychometric properties

The psychometric properties of the SPSS were examined for both samples (Table 2). Model fit indices proved adequate in both the Brazilian sample (χ^2/df = 1.06, SRMR = .05, GFI = .99, TLI = .997, CFI = .99, RMSEA = .014, 90% CI [.000, .029]) and the Portuguese sample (χ^2/df = 0.60, SRMR = .07, GFI = .97, TLI = 1.02, CFI = 1.00, RMSEA = .000, 90% CI [.000, .000]).

Internal consistency, assessed by Cronbach's alpha, showed distinct values across subscales in both countries. In the Brazilian sample, the Open Rejection subscale presented α = .930, Gender Performance α = .810, and Denial of Visibility α = .580, with a total score of α = .870. In the Portuguese sample, the values were α = .926 for Open Rejection, α = .902 for Gender Performance, α = .676 for Denial of Visibility, and α = .910 for total score.

Subscale means indicated similar patterns in both countries, with higher values for Denial of Visibility (Brazil: *M* = 2.13, *SD* = 0.95; Portugal: *M* = 2.67, *SD* = 1.18) and lower values for Open Rejection (Brazil: *M* = 1.42, *SD* = 0.76; Portugal: *M* = 1.53, *SD* = 0.84). The total scale scores were *M* = 1.68 (*SD* = 0.72) for Brazil and *M* = 1.95 (*SD* = 0.85) for Portugal.

Table 2. Psychometric properties of the SPSS by country.

Indicators	Brazil (n = 348)	Portugal (n = 270)
Fit indices		
χ^2/df	1.06	0.60
SRMR	.05	.07
GFI	.99	.97
TLI	.997	1.02
CFI	.99	1.00
RMSEA [90% CI]	.014 [.000, .029]	.000 [.000, .000]
Internal consistency		
Cronbach's Alpha (α)		
OR	.930	.926
GP	.810	.902
DV	.580	.676
Total	.870	.910
Composite reliability (ρ)		
OR	.940	.940
GP	.850	.920
DV	.710	.770
Subscale means		
OR	1.42 (0.76)	1.53 (0.84)
GP	1.70 (0.87)	1.86 (1.00)
DV	2.13 (0.95)	2.67 (1.18)
Total	1.68 (0.72)	1.95 (0.85)

Note. OR = Open Rejection; GP = Gender Performance; DV = Denial of Visibility; CI = Confidence Interval. Means presented as M (SD). All fit indices significant at p < .005.

Table 3 presents the key validity indicators of the SPSS. The Fornell-Larcker criterion was satisfied in both countries, with the Open Rejection (OR) subscale showing the most robust square root of AVE values (Brazil and Portugal: .83). The Average Variance Extracted (AVE) proved adequate for OR (Brazil and Portugal: .92), while the GP (Brazil: .46; Portugal: .63) and DV (Brazil: .37; Portugal: .41) subscales showed values below or near the recommended threshold of .50.

Correlations with the MSALG demonstrated convergent validity, with notable associations between Homopathologization and the OR (Portugal: $r = .52$, $p < .001$) and GP (Portugal: $r = .58$, $p < .01$) subscales. The HTMT indices remained below .85 in the Portuguese sample, while in the Brazilian sample, the GP ratio approached this limit (.85), indicating potential challenges to discriminant validity.

Table 4 presents the analysis of sexual prejudice in relation to sociodemographic variables. Significant gender differences were observed in both samples, with male participants showing higher levels of sexual prejudice in Brazil ($U = 12983$, $p < .05$, $rb = .102$) and in Portugal ($U = 7379$, $p < .05$, $rb = .166$). Regarding sexual orientation, no significant differences were found in either country.

Political positioning showed significant associations in both countries, with right-wing participants presenting higher means in both Brazil ($H(2) = 9.10$, $p < .05$, $\varepsilon^2 = .026$) and Portugal ($H(2) = 7.25$, $p < .05$, $\varepsilon^2 = .027$). Concerning political interest, significant differences were observed only in the Brazilian sample ($H(3) = 11.55$, $p < .01$, $\varepsilon^2 = .033$), where participants with high political interest showed significantly higher levels of prejudice compared to those with no political interest. Religiosity did not demonstrate significant associations with sexual prejudice in either sample.

Table 3. Discriminant and convergent validity of the SPSS by country.

Measure	Brazil (n = 348)			Portugal (n = 270)		
	OR	GP	DV	OR	GP	DV
Fornell-Larcker						
Open Rejection (OR)	**.83**	-	-	**.83**	-	-
Gender Performance (GP)	.78	**.68**	-	.76	**.79**	-
Denial of Visibility (DV)	.74	.71	**.61**	.65	.67	**.64**
Convergent validity						
MSALG total score	.33***	.20***	.32***	.38***	.23**	.39***
Rejection of proximity	.18***	.20***	.22***	.22**	.09	.14
Homopathologization	.24***	.29***	.26***	.52***	.58**	.57***
Modern heterosexism	.19***	.23***	.32***	.30***	.28***	.44***
Support	-.17***	-.25***	-.18***	-.25**	-.45***	-.40***
Extracted variance						
AVE	.92	.46	.37	.92	.63	.41
HTMT Ratio	.82	.85	.84	.81	.73	.69

*Note. Values in bold on the diagonal represent the square root of AVE. OR = Open Rejection; GP = Gender Performance; DV = Denial of Visibility; HTMT = Heterotrait-Monotrait Ratio; AVE = Average Variance Extracted. *p < .05; **p < .01; ***p < .001.*

Table 4. Analysis of sexual prejudice by sociodemographic variables.

Variable	Brazil (n = 348)			Portugal (n = 270)		
	***M* (*SD*)**	**Statistic**	***ES***	***M* (*SD*)**	**Statistic**	***ES***
Gender						
Male	1.70 (0.65)	*U* = 12983*	*rb* = .102	2.16 (0.81)	*U* = 7379*	*rb* = .166
Female	1.60 (0.56)			1.93 (0.65)		
Sexual 0rientation						
Heterosexual	1.67 (0.66)	*H*(2) = 1.53	ε^2 = .004	2.03 (0.71)	*H*(3) = 1.30	ε^2 = .005
Bisexual	1.65 (0.53)			2.11 (0.79)		
Homosexual	1.49 (0.36)			1.96 (0.89)		
Pansexual/Other	—			2.14 (0.75)		
Political positioning						
Left	1.63 (0.64)	*H*(2) = 9.10*	ε^2 = .026	2.09 (0.75)	*H*(2) = 7.25*	ε^2 = .027
Centre	1.57 (0.47)			1.78 (0.74)		
Right	2.12 (0.79)[a]			2.32 (0.74)[a]		
Political interest						
High/Very high	2.03 (0.87)[a]	*H*(3) = 11.55**	ε^2 = .033	1.52 (0.54)	*H*(3) = 5.64	ε^2 = .021
Moderate	1.64 (0.67)			1.87 (0.62)		
Low/Little	1.65 (0.52)			2.08 (0.83)		
None	1.44 (0.38)[b]			2.07 (0.67)		
Religiosity						
Very religious	1.56 (0.40)	*H*(2) = 0.52	ε^2 = .015	2.48 (1.37)	*H*(2) = 1.95	ε^2 = .007
Moderate	1.63 (0.61)			2.06 (0.69)		
Not religious	1.73 (0.74)			1.89 (0.56)		

*Note. Values presented as Mean (Standard Deviation) for the total SPSS score. ES = Effect Size; rb = point-biserial correlation; ε^2 = epsilon squared. Different superscript letters ([a],[b]) indicate groups that differ. *p < .05; **p < .01; ***p < .001.*

Table 5 presents the results of the hierarchical multiple regression analysis predicting sexual prejudice in sport in both countries. In Brazil, Model 1, including basic sociodemographic variables, was not statistically significant, explaining only 1.6% of the variance (R^2 = .016, *F* = 1.86, *p* > .05). Model 2, with the addition of variables related to religiosity, political positioning, and political interest, explained 4.3% of the variance, representing a significant increase ($\Delta R^2 = .027$, $F = 3.18$, $p < .05$). In this model, political interest emerged as the only significant predictor ($\beta = -.130$, $p < .05$). Model 3, incorporating the EMAFLG Total Score, explained 25.7% of the total variance ($R^2 = .257$, $\Delta R^2 = .214$, $F = 98.05$, $p < .001$), with this variable emerging as the strongest predictor ($\beta = -.475$, $p < .001$).

In the Portuguese sample, although Model 1 did not achieve statistical significance as a whole ($R^2 = .024$, $F = 2.17$, $p > .05$), gender emerged as a significant predictor ($\beta = .151$, $p < .05$). Model 2 explained 6.4% of the variance ($R^2 = .064$, $\Delta R^2 = .040$, $F = 3.75$, $p < .05$), with religiosity ($\beta = .170$, $p < .01$) and gender ($\beta = .149$, $p < .05$) as significant predictors. Model 3 explained 11.9% of the total variance ($R^2 = .119$, $\Delta R^2 = .055$, $F = 16.24$, $p < .001$), maintaining religiosity ($\beta = .185$, $p < .01$) and gender ($\beta = .123$, $p < .05$) as significant predictors, with the addition of the EMAFLG Total Score ($\beta = -.256$, $p < .001$).

Table 5. Hierarchical multiple regression analysis predicting sexual prejudice in sport in Brazil and Portugal.

	Brazil (n = 348)			**Portugal (n = 270)**		
Variables	**Model 1**	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
	β	β	β	β	β	β
Age	-.033	-.026	-.039	-.059	-.037	-.035
Gender	.081	.086	.050	.151*	.149*	.123*
Sexual orientation	-.090	-.041	.033	.042	.038	.019
Levels of religiosity		.071	-.018		.170**	.185**
Political positioning		.042	-.005		-.089	-.047
Political interest		-.130*	-.069		-.045	.099
EMAFLG Total Score			-.475***			-.256***
R^2	.016	.043	.257	.024	.064	.119
F for change in R^2	1.86	3.18*	98.05***	2.17	3.75*	16.24***

*Note. Values presented are standardized beta coefficients (β) for each model. EMAFLG = Multidimensional Scale of Attitudes Toward Lesbians and Gays). *p < .05; **p < .01; ***p < .001.*

DISCUSSION

This investigation extends the understanding of sexual prejudice in Portuguese and Brazilian sporting contexts, as well as its associated factors. The three-factor structure of the Sexual Prejudice in Sport Scale (SPSS) – open rejection, denial of visibility, and gender performance – was confirmed in both samples, aligning with findings obtained in Italy (Baiocco et al., 2020). The robust fit indices observed in both contexts support the construct validity of the instrument (Schermelleh-Engel et al., 2003).

In the psychometric analyses, the open rejection and gender performance subscales demonstrated adequate internal consistency, composite reliability, and convergent validity in both countries. The denial of visibility subscale, however, presented limitations regarding discriminant validity in relation to gender performance. These difficulties were more pronounced in the Brazilian sample, where Cronbach's alpha values (.58) and average variance extracted (.37) fell below recommended parameters. According to Henseler et al. (2015), such challenges can be attributed to conceptual overlap between the factors, making their empirical distinction difficult. These methodological concerns constitute a limitation of the present investigation and suggest the need for refinement of the scale in future studies. The original structure proposed by Baiocco et al. (2020), despite these limitations, maintains its utility for evaluating sexual prejudice in sport across different cultural contexts.

The lowest mean scores were observed in the open rejection factor in both countries, suggesting a lower prevalence of explicit expressions of sexual prejudice. This result corroborates the perspective that overt manifestations of prejudice face increasing social disapproval in contemporary Western societies (Crandall and Eshleman, 2003). Denial of visibility, on the other hand, presented the highest means in both the Portuguese and Brazilian samples. This pattern indicates a persistent resistance to the recognition of LGBT athletes in the sporting culture of both countries, even when more explicit expressions of prejudice are less frequent.

The convergent validity of the SPSS was established through significant correlations with the Multidimensional Scale of Attitudes Toward Lesbians and Gays (MSALG) in both countries. In the Portuguese sample, the strong correlation between the open rejection subscale of the SPSS and the homopathologization dimension of the MSALG (r = .52) was particularly notable. The correlations in the Brazilian sample, although significant, presented lower magnitudes (ranging from r = .18 to r = .33), suggesting possible cultural differences in the manifestation and expression of sexual prejudice between the two contexts.

Significant gender differences were identified in levels of sexual prejudice. Male participants demonstrated higher scores, corroborating results from previous studies (Sartore and Cunningham, 2009; Cunningham and Melton, 2013). This pattern reflects the traditionally male dominance of the sporting environment, where adherence to hegemonic gender norms holds substantial value (Sartore-Baldwin, 2013). A distinctive aspect between the samples refers to the scope of these differences: in the Brazilian sample, they were significant only in the open rejection (rb = .102) and gender performance (rb = .135) subscales, while in the Portuguese sample, the difference was also significant in the total scale score (rb = .166).

Analyses related to sexual orientation did not reveal significant differences between groups in either country, partially contrasting with the findings of Baiocco et al. (2020). The absence of significant variations may indicate two distinct phenomena: the possible internalization of heteronormative beliefs among non-heterosexual athletes in sporting environments or the development of more inclusive attitudes among heterosexual athletes. In the Portuguese sample, a moderate positive correlation was observed between sexual orientation and prejudice (r = .219), suggesting higher levels of prejudice among heterosexual athletes. In the Brazilian sample, this correlation was not significant, indicating distinct dynamics in the experiences and expressions of sexual identity in the two cultural contexts.

Regarding religiosity, the results expand the literature associating traditional religious beliefs with negative attitudes toward sexual minorities (Cunningham and Melton, 2012). Highly religious participants in the Portuguese sample demonstrated elevated levels of prejudice, particularly in the open rejection dimension. In the Brazilian sample, although differences did not reach statistical significance (ε^2 = .015), a similar trend was observed. This pattern establishes a relationship between increased religiosity and greater manifestation of prejudice, especially in the domains of open rejection and denial of visibility.

Results concerning political orientation presented consistent patterns between the two countries. In both Brazil (ε^2 = .026) and Portugal (ε^2 = .027), participants identified with right-wing political positions demonstrated higher levels of sexual prejudice. A notable difference, however, was observed: while in the Portuguese sample the left-wing group presented high scores in the open rejection dimension, this phenomenon was not found in the Brazilian sample. This contrast introduces important nuances in relation to previous studies that consistently link conservative political positions to negative attitudes directed at sexual minorities (Cunningham and Melton, 2012; Piedra et al., 2017; Hoyt et al., 2018).

A significant contrast between countries emerged in the analysis of political interest. In the Brazilian sample, participants with greater political interest presented higher levels of prejudice (ε^2 = .033), while in Portugal an inverse relationship was observed, with lower levels of political interest correlated with increased sexual prejudice. This divergence may reflect the different political and social dynamics present in the two countries, particularly regarding the framing of LGBT issues in contemporary political discourse.

The significant associations between sexual prejudice and political-religious variables in both countries highlight the importance of ideological factors in shaping attitudes toward sexual minorities (Anderson and Mowatt, 2013; Piedra et al., 2017; Ferros and Pereira, 2021). Higher levels of religiosity and right-wing political positioning corresponded to greater manifestations of prejudice, reflecting traditional conservative principles incorporated in right-wing religious and political ideologies.

The hierarchical multiple regression analysis demonstrated that incorporating political positioning, religiosity, and attitudes toward gays and lesbians substantially increased the predictive power of the model, beyond basic demographic variables. In the Brazilian sample, attitudes toward gays and lesbians emerged as the strongest predictor (β = -.475), explaining an additional 21.4% of variance. In the Portuguese sample, in addition to attitudes toward gays and lesbians (β = -.256), religiosity (β = .185) and gender (β = .123) remained significant predictors in the final model, suggesting a more complex interaction of sociocultural factors in the formation of sexual prejudice in this context.

CONCLUSIONS

This investigation provides important evidence regarding sexual prejudice in the sporting context in two Portuguese-speaking countries, revealing both similarities and significant differences. The Sexual Prejudice in Sport Scale (SPSS) proved to be a valid instrument in both contexts, maintaining the three-factor structure originally proposed by Baiocco et al. (2020), with satisfactory psychometric properties.

The results revealed a consistent pattern of greater sexual prejudice among male athletes in both countries, reinforcing the understanding of sport as a traditionally heteronormative environment. Right-wing political positioning also emerged as a significant predictor of negative attitudes in both countries, albeit with distinct manifestations across different dimensions of prejudice. These findings contribute to the understanding of ideological factors that influence attitudes toward sexual diversity in the sporting context.

Important differences between the two countries were identified, especially regarding the role of religiosity and political interest. In the Portuguese sample, religiosity proved to be a significant predictor of sexual prejudice, while in Brazil this relationship did not reach statistical significance. Regarding political interest, contrasting patterns emerged: in Brazil, greater political interest was associated with higher levels of prejudice, while in Portugal the trend was opposite. These variations highlight the importance of considering sociocultural specificities in understanding and addressing sexual prejudice.

The practical implications of this study are diverse. For the Brazilian context, the results suggest the need for educational programs that promote more effective dialogue between political participation and inclusive attitudes in sport. In the Portuguese context, interventions targeting the intersection between religiosity and prejudice seem particularly relevant. In both countries, strategies to transform traditionally masculine sporting cultures into more welcoming environments for sexual diversity are necessary.

The study presents methodological limitations that should be considered. The use of non-probabilistic convenience samples in both countries restricts the generalization of results. Differences in the demographic composition of the samples – with female predominance in Brazil (60.6%) and male predominance in Portugal (58.5%) – may have influenced some of the observed contrasts. Additionally, the denial of visibility subscale presented reliability indices below recommended values, particularly in the Brazilian sample.

Future research should employ more robust sampling methods and include greater diversity of participants for better understanding of the dynamics of prejudice in sport. Revision of the denial of visibility subscale is also necessary to improve its psychometric properties. More comprehensive cross-cultural studies could explore the underlying reasons for the observed differences between Brazil and Portugal, analysing how macrostructural factors – including public policies and legal rights – influence attitudes in the sporting context.

AUTHOR CONTRIBUTIONS

This manuscript is a collaborative work of two authors who reviewed and approved its final version. The contribution of each author includes: Vivianne Oliveira Gomes: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. Henrique Pereira: Conceptualization, Formal analysis, Methodology, Supervision, Writing - review & editing.

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ORIGINAL ARTICLE

Timeouts and psychological momentum in volleyball

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ABSTRACT

Coaching strategies reflect the belief that volleyball is a momentum-driven sport. This study investigated whether timeouts are associated with success for the subsequent play (i.e., a "*sideout*") using archival data from Women's Division I Volleyball in the United States. Sideout rates following 2529 timeouts from 234 matches were compared to the sideout rates of typical play from 3867 plays taken from 25 randomly selected matches. Results showed that the sideout rate for points following a timeout was similar to the sideout rate of typical play, suggesting that timeouts could be employed to reset performance. Additionally, the sideout rate was higher after timeouts when they were taken early in a scoring run as opposed to later in a run, and when the score difference is within 3 points, indicating that timeouts could thwart the buildup of momentum. These results have implications for the understanding of psychological momentum and coaching.
Keywords: Psychological momentum, Volleyball, Timeout, Coaching, Sports psychology.

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INTRODUCTION

Volleyball is a rapidly growing sport, with more than 800 million participants worldwide (Peter, 2024). It surpassed basketball as the most popular sport for high school girls in the United States in 2015; 96 percent of all National Collegiate Athletic Association (NCAA) schools and over 1,800 colleges and universities sponsor a women's volleyball team (NCSA, n.d.). As the sport gains broader attention, the common coaching practice of using timeouts to interrupt psychological momentum needs to be empirically examined. Although timeouts are available to both teams in volleyball, they are taken almost exclusively by the offensive team when they fail to execute a "*sideout*" play to earn a point (i.e., when they are on the losing side of the momentum shift). This study critically evaluated this strategy and examined the broader implications for the understanding of psychological momentum, particularly coaching strategies as interventions to interrupt psychological momentum.

Psychological Momentum (PM)

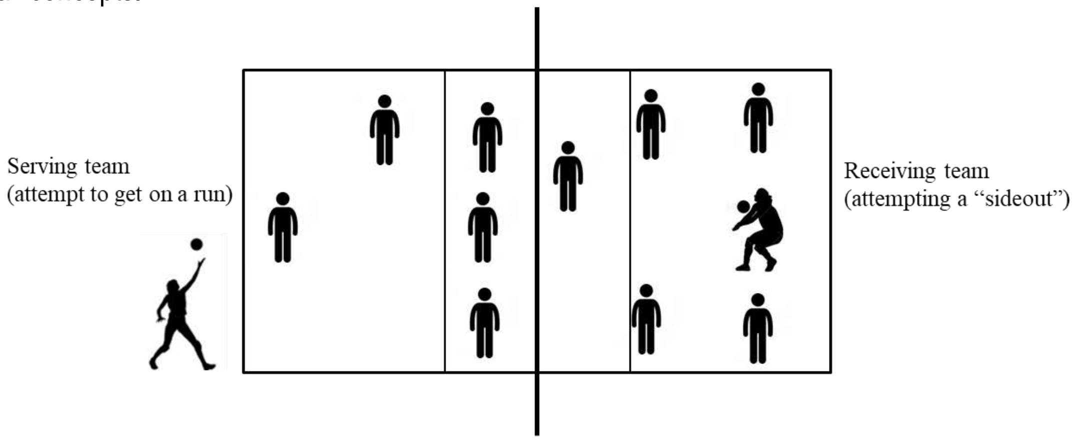
Although different conceptions of Psychological Momentum (PM) exists, we follow the Iso-Ahola and Dotson's (2014) view that it is a perceptual phenomenon during which an individual performer or team has some initial success and builds a sense that they will continue to do well. The positive PM of one side is also felt by their opponent, whose initial lack of success both fuels their opponent's positive PM and their own downward spiral (negative PM). More specifically, PM represents a display of sequential dependence, whereby initial success leads to subsequent success (positive PM), and initial failure leads to subsequent failure (negative PM). PM has different qualities, such as frequency (how often PM occurs; a team may gain PM at various times throughout a match), intensity (how strong is the PM; a team may win a point after a long and hard fought rally), and duration (how long PM lasts; a team may ride a wave of momentum for many consecutive points during a game).

Participants (players and coaches) go to great lengths to achieve positive PM and interrupt negative PM. For example, football coaches take timeouts before kickers attempt game ending field goals (Goldschmied et al., 2010; Hsu et al., 2019), basketball coaches take timeouts to ice free throw shooters or when being outscored by opponents (Mace et al., 1992; Goldschmied et al., 2023; Roane et al., 2004), and coaches would urge teammates to give more opportunities to a player with the "*hot hand*" (e.g., Bar-Eli et al., 2006; Gilovich et al., 1985; Raab et al., 2012; Yaari & Eisenmann, 2011).

Patterns of timeout-taking behaviour exhibited by coaches suggest that coaches believe that PM exists and could be interrupted by using timeouts. If initial success leads to subsequent success, then coaches' use of timeouts can represent an attempt to thwart the opponent's positive PM and end one's own negative PM (Hartigh & Gernigon, 2018). In volleyball, the effectiveness of this strategy can be measured by whether the team taking a timeout wins the point following the timeout. If one wins the point following the timeout, then one has made a successful (albeit perhaps temporary) attempt at interrupting the ongoing PM.

Psychological momentum in volleyball

In volleyball, the serving team plays defence first while the team receiving the serve plays offense first (i.e., they have the first opportunity to execute an offensive play). A *sideout* is achieved when the team receiving the serve wins the point. (We note that we are using the term *sideout* to refer to this specific point, and not the outdated scoring system that was employed until to the late 1990s when it was replaced by the current rally scoring system). Only the serving team can win consecutive points by preventing the receiving team from completing a sideout. Therefore, only the serving team can gain positive PM, while the receiving team is left attempting to interrupt that momentum and preventing negative PM by avoiding losing several points in a row. Although available to both teams, timeouts are taken almost exclusively (99.72% of the time in our dataset) by the team attempting to execute a sideout. This strategy can be interpreted as the use of timeouts to interrupt the opponent's positive PM and one's own negative PM. See Figure 1 for a summary of basic volleyball concepts.



Note. The serving team can create positive PM by winning consecutive points (i.e., "getting on a run"). Scoring runs only occur for the serving team. The receiving team uses timeouts as a strategy to achieve a sideout. If the receiving team successfully completes a sideout, then it becomes the serving team.

Figure 1. Volleyball basics.

Taking the position that timeouts could be effective at interrupting PM, we made the following predictions. *Hypothesis 1*: The sideout rate following a timeout would be higher than the sideout rate of typical play (when there is no timeout), which reflects Iso-Ahola and Dotson's [2014] conception of PM as a perceptual phenomenon. *Hypothesis 2*: The sideout rate for timeouts taken before a team establishes momentum should be higher than the sideout rate of timeouts taken after a team establishes momentum. That is, the sideout rate for timeouts taken before a team gets on a scoring run (scores three or less consecutive points) should be higher compared to the sideout rate when a team establishes a run (scores four or more consecutive points). *Hypothesis 3:* The sideout rate for timeouts taken while the outcome of the game is still within reach for both teams (score difference of three points or fewer) should be higher compared to the sideout rate for timeouts when the outcome of the game is more out of reach (score difference of 4 points or more). Hypotheses 2 and 3 specifically addresses the duration aspect of PM in the Iso-Ahola and Dotson model of PM. We examined these hypotheses using NCAA Division 1 archival data.

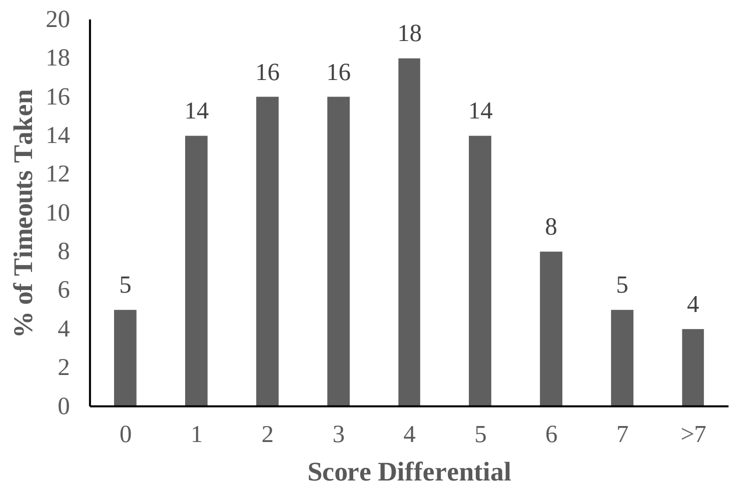
METHOD

We examined archived play-by-play for all matches played during a full season in the Big10 Conference in 2013 (available on stats.ncaa.org). We selected the Big10 Conference because it is considered the most competitive conference for Women's Division I Volleyball. In particular, the national championship match for this season featured two teams from the Big10 Conference (Penn State and Wisconsin). The archived play-by-play records document the name of serving team, the score at the start of the point, and the outcome of the point. The play-by-play records also note if a timeout was taken before the point, and if there was a timeout, which team requested the timeout. These records were manually extracted and coded into an Excel file by a research assistant under the supervision of the first author, who conducted checks to ensure accuracy of the data extraction. We coded 234 matches, where 2529 timeouts occurred. In the final analysis, we excluded seven timeouts because they were taken by the serving team (not by the team attempting the sideout). These seven timeouts represented 0.28 percent of all timeouts taken. Thus, the final total sample included 2522 timeouts. In addition to coding plays that involved timeouts, we also coded plays that did not involve timeouts ("*typical play*") to serve as the comparison group. We randomly selected 25 matches in the same conference and year and coded outcomes of 3867 typical plays to serve as the comparison group for timeouts.

RESULTS

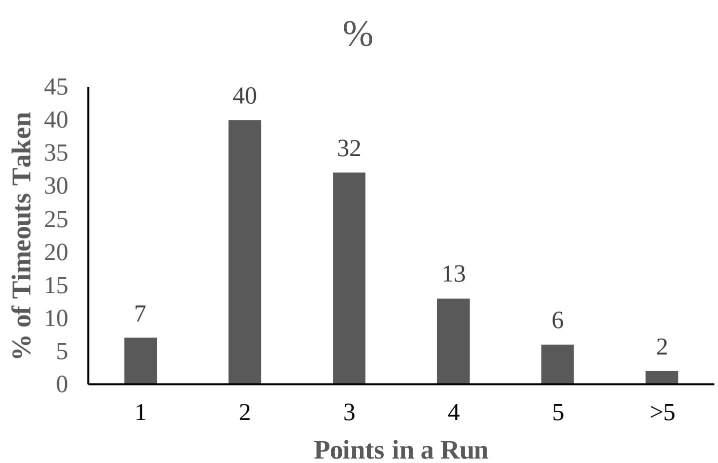
General timeout patterns

Coaches used timeouts when the score differential is low (51% of timeouts taken when the score differential is three points or fewer; 78% of timeouts taken when score differential is 5 or fewer). In addition, coaches tend to use timeouts early in scoring runs (79% of timeouts taken when the run is between 1 and 3 points; 92% of timeouts taken when the run is between 1 and 4 points). See Figures 2 and 3 for details.



Note. The majority of timeouts are taken when the score difference is between 1 and 5 points.

Figure 2. Percent of timeouts taken by score differential.



Note. The majority of timeouts are taken when the serving team scores two or three points in a row.

Figure 3. Percent of timeouts taken by points in a run.

Effectiveness of timeouts

We employed chi-square goodness of fit tests to assess potential differences between the sideout rate after timeouts compared to typical play, because this test allowed us to compare observed frequencies with expected frequencies. We also report Cohen's ω, which follow the conventional threshold of .10 for small, .30 for medium, and .50 for large effect sizes (Cohen, 2016). The team receiving the serve won the point (i.e., completed a successful side out) 58.08% of the time in the course of typical play when there was no timeout (N = 3867). In other words, the sideout rate of typical play was 58.08%. Surprisingly, the sideout rate for points following a timeout was 58.6%, which is not different from the sideout rate of typical play, χ^2 (1, N = 2522) = 0.33, p =.56, ω = .001. However, timeouts are effective when they are taken when the score difference is within 3 points (sideout rate = 59.9%) compared to when the difference is beyond 3 points (sideout rate 54.1%), χ^2 (1, N = 1986) = 26.62, p <.001, ω = .60. Furthermore, timeouts also tend to be more effective when taken early in a run (between 1-3 points; 61.0%) as opposed to later in a run (>3 points; 56.3%), χ^2 (1, N = 861) = 11.35, p <.001, ω = .39. See Table 1 for a comparison of effectiveness of timeouts across various scenarios.

Table 1. Comparisons of sideout rates.

	n	Sideout %	χ^2	*p*	ω
Typical Play (Expected Rate)	3867	58.08			
Various situations compared to typical play					
After timeout	2522	58.64	0.33	.56	.01
Score difference 0-3	1252	61*	4.45	.035	.13
Score difference >3	1270	56.3	1.65	.20	.05
Run of 1-3	1986	59.9	2.61	.11	.06
Run of >3	536	54.1	3.48	.06	.15
Various situations compared to each other					
Run of 1-3 vs. Run above 3	1986	59.9 vs. 54.1**	26.62	<.0001	.60
Score difference 0-3 vs. above 3	861	61.0 vs. 56.3**	11.35	.001	.39

Note. Timeouts are effective when they are taken when the score difference is within 3 points. Timeouts also tend to be more effective when taken early in a run as opposed to later in a run. However, there is no general effect of taking timeouts when comparing all points played after a timeout and points during typical play.

DISCUSSION

The data showed that the rate of successful sideouts following a timeout is no different than the sideout rate of typical play, indicating no support for Hypothesis 1. However, the interpretation of this fact may benefit from some nuance. From one perspective, one can claim that timeouts are not effective because they do not increase the rate of sideout above the rate of sideout for typical play. On the other hand, the use of timeouts brings the sideout rate back to be equivalent to the rate of typical play, which can be interpreted in favour of timeout's effectiveness. Additionally, it seems that timeouts help the receiving team maintain their advantage as the receiving team. This pattern could be interpreted as a change in momentum considering that teams that take the timeout are typically at a disadvantaged position from the perspective of psychological momentum (i.e., 99.72% of the time, timeouts are taken by the team that needs to execute a sideout play). Therefore, it could be considered a success if teams are able to return to their normal level of functioning. That is, timeouts could be perceived as effective for stabilizing and resetting team performance.

The evidence for the effectiveness of timeouts to curb psychological momentum is much stronger in situations relating to scoring runs and scoring differentials. We found that a timeout taken prior to the opponent scoring

3 or fewer points in a row is more effective than a timeout taken after the opponent scores 4 or more points in a row, supporting Hypothesis 2. The same is true for when timeouts are taken when the score difference is less than or equal to 3 points compared to more than 3 points, supporting Hypothesis 3. Reflecting these trends, it appears that coaches understand the importance of these critical junctures. For example, 79% of timeouts were taken by coaches after the other team has scored 3 or fewer points in a row. However, only 51% of timeouts were taken when the score differential was 3 or fewer points. Our data suggests that it might be prudent for coaches to use their timeouts not only to deter scoring runs, but to also when the scores are well within reach in order to maximize timeout's effectiveness. This suggestion is also supported by previous works that show that athletes tend to exert more effort at the start of PM and decrease effort as PM continues (Briki et al., 2013).

The results about the specific scenarios in which timeouts are most effective also indicate that timeouts might be more effective at preventing opponent's buildup of PM rather than thwarting PM after it has begun. Two findings supported this notion. In one instance, timeouts tended to be more effective when coaches used them while the score differential was small as opposed to when the margin was large (i.e., while the game is still within reach). In addition, timeouts tended to be more effective when coaches used them early in a scoring run as opposed to late in a scoring run (i.e., before the other team has gained momentum). Relatedly, strategic use of timeouts may be especially important in matches where the two teams competing are evenly matched, as indicated by score differential and consecutive points scored. Taken together, these findings offer some support for the strategy of using timeouts to interrupt and/or prevent the development of PM.

Limitations and future directions

These results need to be considered in light of some limitations. For one, all data were based on retrospective archival data, so speculations about the causal effects of timeout need to be considered carefully. There are many factors that could lead to performance outcomes following timeouts, such as individual and team performance efficiency (e.g., Drikos et al., 2024; Sanjaykumar et al., 2024), coaching mastery in handling timeouts, coach-team dynamics (Huynh et al., 2020), and training that these data did not consider. Additionally, these data were taken from one season play from Women's NCAA Division I volleyball in the Big 10 Conference. This is considered to be one of the highest levels of women's volleyball within the United States. As such, these findings might not translate to other levels of play, such as in youth volleyball (where the base sideout rate is expected to be much lower) or international men's volleyball (where the base side out rate is expected to be much higher).

Another limitation is that statistical analyses did not control for the program strength of each team. Sideout rates for each team were compared to the conference average without consideration of that team's relative competitiveness within the conference. For example, it would be expected that teams playing at a lower level would have less chance of siding out than teams at a higher level. It is possible that less competitive teams are consistently taking more timeouts (i.e., against stronger teams) and so the measured sideout rate after timeouts is closer to that of lower-performance teams than an average for the conference. Using past tournament placements or winning percentage could provide a valid indication of program level.

Instances in which teams took two timeouts before one sideout were also uncontrolled for. In volleyball, each team has two timeouts per set, so it is possible that timeouts were nested within one scoring run for the serving team. These potential occurrences were not recorded in the data and it is possible that they carry nesting effects. Despite these limitations, the paper offers an interesting and practical examination of how timeouts could potentially influence psychological performance in competitive sporting competitions.

CONCLUSION

Volleyball is a widely popular sport with more than 800 million participants worldwide. As such, research on coaching strategies involving the use of timeouts have implications for participants and the study of psychological momentum more broadly. The study's findings generally support the use of timeouts to curb psychological momentum. Timeouts appear to be able to reset teams back to their baseline line level, but do not help them exceed typical levels of performance generally. However, situational factors may modulate the effectiveness of timeout use. For example, timeouts taken earlier in a scoring run and when the score is close between the two opponents appear to be more effective. These findings have implications for how coaches might strategically employ timeouts to maximize team performance. However, further research is needed to replicate and extend these findings.

AUTHOR CONTRIBUTIONS

Ho Phi Huynh: conceptualization, methodology, formal analysis, investigation, data curation, writing - original draft, writing - review and editing, visualization, supervision. Joel Goh: writing - original draft, writing - review and editing. William Condon: conceptualization. Kristin Layous: writing - review and editing.

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No potential conflict of interest was reported by the authors.

DATA AVAILABILITY

The data that support the findings of this study are available upon reasonable request from the corresponding author.

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ORIGINAL ARTICLE

Psychological characteristics of pre-match competitive Tai Chi athletes

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ABSTRACT

Background: The aims were to investigate and compare the pre-match psychological characteristics in both genders and three levels of competitive Tai Chi athletes. Methods: They were 40 competitive Tai Chi athletes (20 males and 20 Females), aged 19-24 years old at the school of physical education of Zhengzhou university, China. Results: There was no significant difference in the pre- match psychological characteristics between genders. The study found that the high-level competitive Tai Chi athletes were better than the low level of Tai Chi athletes in each dimension of the questionnaire, and there were significant differences in the five-factor mindfulness questionnaire, contest anxiety questionnaire and trait motor self-confidence scale. There was no significant difference in the positive mood between different sports levels in the mood measurement scale, but there was a significant difference between the national and the second level athletes in the negative mood dimension. There was a significant difference in the total score of mood disturbance between first and second level. Conclusions: there was no significant between males and females in each level. The five-factor mindfulness questionnaire mood measurement scale, contest anxiety questionnaire and trait motor self-confidence scale of national level athletes were significantly higher than other levels.
Keywords: Psychological quality, Competitive Tai Chi athletes, Pre-Match psychological characteristics.

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INTRODUCTION

The importance of pre-match psychological preparation for competitive Tai Chi athletes has been emphasized in multiple studies. The content and principles of pre-match preparation for Tai Chi athletes were discussed, including pre-match psychological preparation and preparation procedures. The importance of psychological preparation was emphasized (Qiu, 2001), and it was pointed out that the characteristics of Tai Chi and the requirements of the competition make psychological factors have a significant impact on athletes' performance (Li et al., 2024; He, 2016). This indicates that athletes of different sports will experience certain psychological tension and state adjustment before the competition (He, 2016). Further emphasis was placed on the impact of psychological state on athletes' performance, and relevant suggestions were proposed. (Yao, 2001) emphasized the importance of psychological characteristics of excellent athletes, pre competition psychological preparation, and how to improve athletes' competitive level through psychological regulation (Ge et al.,2019; Lu, 2014; Zhang, 2013). In summary, the psychological characteristics of competitive Tai Chi athletes before the competition are crucial for their performance in the competition. Through psychological training and preparation, athletes can maintain a good competitive state in high-pressure competition environments and fully unleash their technical and skill potential.

Pre-match psychological characteristics refer to the mental state and characteristics of athletes before the start of a competition or competitive activity. These characteristics directly affect the athlete’s performance in the competition, ability to cope with pressure, and final competitive results (Qu et al., 2023). The innate unconditioned reflex instinct in psychological characteristics can provide physiological driving force or the formation of mental state. The acquired conditioned reflex instinct, skills, physical fitness and other abilities can provide the potential possibility of completing tasks for the mental state, while personality can provide the potential for completing tasks. Accomplishing group and long-term goals provides individuals with unique habitual attitudes and behavioural responses (Erin et al., 2022). The pre-match psychological characteristics in this article refer to the emotional experience of athletes caused by various internal and external stimuli and the athletes' cognition of various stimuli before participating in the competition. Psychological adjustment ability refers to the ability of athletes to adjust their mental state in a timely manner according to the situation during the competition. Good mental adjustment ability can help athletes maintain a positive and optimistic attitude when encountering difficulties and setbacks, so as to perform at their best level. Questionnaire measurement revealed that athletes often face tremendous pressure during competitions, which may come from winning the competition, not wanting to lose the competition, or fear of expectations and pressure. This pressure can lead to anxiety and tension, affecting athlete performance (Tan, 2023).

Previous research using the Eysenck Personality Scale found that competition anxiety can manifest as nervousness, worry, restlessness, and even nausea. This emotional state may affect athletes' attention and execution abilities (Peter et al., 2023). Previous research has found through interviews and observations that competitive athletes' confidence levels are critical to their performance. Under confidence may lead to poor performance, while overconfidence may also lead to problems (Huang et al., 2023). Previous studies combined qualitative and quantitative research methods, from in-depth interviews to biofeedback to psychological tests, to gain a more comprehensive understanding of athletes' pre-match psychological characteristics and use multi-level and multi-angle research methods to reveal the psychological pressure athletes may face before competition. and challenges (Wang, 2010; Xuemaleg, 2023). Other studies have shown that social and emotional factors play a key role in psychological problems. By understanding the social support system and emotional state of athletes, factors related to psychological problems can be accurately identified. Multidisciplinary research provides a more comprehensive perspective, combined with the knowledge of sports psychology, neuroscience and biology can help to deeply understand the psychological mechanism of athletes. (Emily et al., 2023; Yu et al., 2023; Katherine et al., 2022; Kearnan et al., 2022; M.SC et al., 2022).

Meta-analysis has been found that mindfulness can effectively improve sports performance, reduce sports anxiety, and enhance self-efficacy. Mindfulness emphasizes comprehensive awareness and acceptance of the current situation, which can be seen as a mindset of facing challenges and overcoming difficulties. Explored the potential role of mindfulness in improving athletic performance. Introduce the principles and contents of mindfulness training, review the research progress of mindfulness training at home and abroad, especially the practical application and achievements of mindfulness training in the field of competitive sports (Zhang, 2017). Mindfulness training can not only alleviate athletes' psychological pressure, but also help athletes maintain their best state during training (Wang, 2019). Mindfulness training has a positive effect on systematically cultivating and improving the competition focus ability of excellent athletes (Zhang, 2017). Mindfulness training can improve the attention and emotional regulation ability of young athletes (Guo et al., 2021). Mindfulness training, as an emerging psychological intervention method, is widely used in various fields (Jie, 2024). Mindfulness also has different levels of intervention effect in sports competition.

According to the current situation and trend of Wushu competition, combined with the characteristics of Tai Chi, this study starts from the personality and psychological characteristics of competitive Tai Chi athletes, and measures the emotional experience of athletes caused by internal and external stimuli and athletes' cognition of various stimuli before participating in the competition through five-factor mindfulness questionnaire (Si et al., 2014), mood measurement scale (Zhang , 2013), contest anxiety questionnaire (Martens, 1977) and trait motor self-confidence scale (Yuan , 2005). Objectives of the research were to investigate and compare the pre-match psychological characteristics between both genders and three levels in competitive Tai Chi athletes.

MATERIAL AND METHODS

This study was observational and Quasi-Experimental Designs, Athletes from Zhengzhou University in Zhengzhou, China, who would participate in the "*2024 National Wushu Taolu Championships*" from 22 to 29 June, 40 competitive Tai Chi athletes.

Participants

This study selected 40 competitive Tai Chi athletes who met the inclusion criteria, including 20 females and 20 males, to ensure the gender balance. Athletes from Zhengzhou University in Zhengzhou, China, who would participate in the "*2024 National Wushu Taolu Championships*" from 22 to 29 June. There were differences in the competitive level of Tai Chi athletes; National, first and second level.

Data collection procedure

The research of this study was to measure the psychological characteristics of competitive Tai Chi athletes through the five-factor mindfulness questionnaire, the contest anxiety questionnaire, the mood measurement scale and the trait motor self-confidence scale and evaluate the psychological characteristics of different competitive Tai Chi athletes before the competition. The collected data was prior to the collection date, before collecting the date, all were tested reliability by test-retest.

Instruments

There were 4 questionnaires in this study including. The Five-Factor Mindfulness Questionnaire, Mood Measurement Scale, Contest Anxiety Questionnaire, Trait Motor Self-Confidence Scale. The details are as follows.

Five-Factor Mindfulness Questionnaire

The five-factor mindfulness questionnaire has a total of 39 questions, using a five-point Richter score, (from match to non-compliance with the score of 1-5 points), some questions are positive scores, some questions are reverse scores, the higher the score, the more obvious the effect of mindfulness training, and vice versa. In this study, the reliability of the mood measurement scale was 0.93.

Mood Measurement Scale

The study used the Chinese Mood Measurement Scale revised by Zhu Beili (1995) to evaluate the changes in the mood state of the test athletes before and after the intervention. The mood measurement scale uses a 5-point Richter score, but the corresponding score is from 0 to 4, and the sum of the seven dimensions plus 100 is the sum of the individual's mood states. In this study, the reliability of the mood measurement scale was 0.92.

Contest Anxiety Questionnaire

The study employed the contest anxiety questionnaire, which divides anxiety into three components: cognitive anxiety, somatic anxiety, and a "*related component*" – self-confidence. Self-confidence, which is often the opposite of cognitive anxiety, was another important factor in managing stress. To score CSLA-2, all points for each item except item 14 were calculated as indicative value, as item 14 was where you "*reverse*" the score. In this study, the reliability of the contest anxiety questionnaire was 0.91.

Trait Motor Self-Confidence Scale

The trait motor self-confidence scale was used to measure athletes' confidence level. Participants answer the questions on a 3-scale scale, with a minimum score of 10 points and a maximum score of 40 points. In this study, the reliability of the Trait Motor Confidence Scale was 0.91.

Data analysis

The demographics of the participants were presented as mean and standard deviation including age, weight, height, training duration, sports training duration, frequency of Sport training. Frequencies or numbers described the sports level and gender of the participants. Five-Factor Mindfulness Questionnaire, the contest anxiety questionnaire, the trait motor self-confidence scale, and the mood measurement scale were also expressed as mean and standard deviation. Multivariate ANOVA was used to compare athletes of different genders and levels. Evaluate the normal distribution of all variables by Shapiro-Wilk test, a statistical analysis at .05.

RESULTS

The baseline of characteristics showed that there were no significant differences between the participants in the two groups of competitive Tai Chi athletes including age, weight, height, training experience, training period, training frequency. Only weight and height were significant differences. Table 1.

As can be seen from Table 2, the higher the score of the five-factor mindfulness questionnaire, the more obvious the effect of mindfulness training, and the lower the negative it was. A higher score on the mood measurement scale indicates a negative state of mind for the athlete and vice versa. Higher scores on the contest anxiety questionnaire indicate higher cognitive and somatic anxiety and state self-confidence. The higher the exercise self-confidence score, the more confident the subject was.

Table 1. Characteristics of competitive Tai Chi athletes.

Characteristics	Male Number	Female Number	Total
National athlete	4	4	8
First level athlete	6	6	12
Second level athlete	10	10	20
	Male Mean (SD) (n = 20)	**Female Mean (SD) (n = 20)**	***p* - value**
Age (year)	20.55 (0.92)	20.32 (0.99)	.22
Weight (Kg)	71.22 (5.24)	55.21 (2.33)	.002**
Height (cm)	171.22 (2.44)	160.55 (2.32)	.002**
Training duration (years)	4.55 (0.98)	4.63 (0.77)	.12
Sports training duration (hours/day)	6.21 (1.11)	6.11 (1.22)	.72
Frequency of Sport training (days/week)	5.11 (1.75)	5.27 (1.55)	.77

*Note. **p < .05, significant at .01.*

Table 2. Comparison of the outcome measurements of competitive Tai Chi athlete between gender.

Outcome measurements	Mean (SD)		*p* - value	Total (n = 40)
	Male (n = 20)	Female (n = 20)		
Five-Factor Mindfulness Questionnaire				
Observe	23.67(4.33)	23.83(4.32)	.471	23.72(4.10)
Description	21.58(4.03)	21.57(4.36)	.486	21.57(4.11)
Act consciously	22.42(3.75)	22.17(3.54)	.504	22.24(3.63)
non-judgment	21.42(5.09)	21.33(4.16)	.571	21.37(4.77)
Not reacting	21.83(3.19)	21.91(3.06)	.719	21.87(3.10)
Total	110.92(4.23)	110.81(4.26)	.882	110.85(4.24)
Mood Measurement Scale				
Positive mood	21.50(8.02)	21.47(8.83)	.607	21.48(8.07)
Negative mood	29.96(8.82)	29.53(8.61)	.283	29.72(8.77)
Total mood disturbance total score	108.46(20.43)	108.06(22.63)	.564	108.33(21.57)
Contest Anxiety Questionnaire				
Cognitive status anxiety	22.83(1.15)	22.83(1.12)	.627	22.83(1.14)
Somatic state anxiety	22.41(1.77)	22.48(1.34)	.695	22.45(1.55)
State self-confidence	23.83(1.62)	23.87(1.55)	.566	23.85(1.57)
Total	23.02(1.24)	23.06(1.22)	.605	23.04(1.22)
Trait Motor Self-Confidence Scale				
Trait motor task confidence	17.68(5.83)	17.83(5.18)	.921	17.75(5.46)
Trait sports coping with self- confidence	21.13(8.80)	21.63(8.57)	.655	21.44(8.66)
Total sports self-confidence score	29.81(13. 40)	28.93(12.33)	.847	29.85(12.99)

*Note. *p < .05, significant at .05.*

As can be seen from Table 3, there was no significant difference in the four scales between athletes of different genders and different sports levels. (p > .05)

As can be seen from Table 4, competitive Tai Chi athletes at different levels of exercise showed significant differences in the following items. In each dimension of the five-factor mindfulness questionnaire, national level athletes scored significantly higher than first and second level athletes. In terms of mood level, there was a significant difference between the national athletes and the second level athletes in terms of negative mood. There was a significant difference between first level and second level athletes in total mood disturbance total score. There were significant differences in competition anxiety level and the trait motor self-confidence scale.

Table 3. Comparison of the outcome measurements of competitive Tai Chi athlete between gender in each level.

Variable	Athletic ratings	Segment items	Male Mean (SD)	Female Mean (SD)	*p* - value
Five-Factor Mindfulness Questionnaire	National (n = 4)	Observe	23.53(0.32)	23.23(1.12)	.712
		Description	22.57(0.36)	22.32(1.33)	.532
		Act consciously	23.37(0.54)	23.28(1.33)	.529
		non-judgment	22.63(0.16)	22.42(1.22)	.424
		Not reacting	22.71(0.06)	22.42(0.06)	.450
		Total	114.81(0.33)	113.67(1.02)	.277
	1st level (n = 6)	Observe	23.03(1.12)	22.93(1.12)	.612
		Description	22.12(1.33)	21.92(1.33)	.514
		Act consciously	23.08(1.33)	22.88(1.33)	.536
		non-judgment	22.02(1.22)	21.82(1.22)	.416
		Not reacting	22.32(0.06)	22.12(0.06)	.422
		Total	112.57(0.32)	111.67(0.88)	.371
	2nd level (n = 10)	Observe	22.02(3.32)	21.73(3.32)	.633
		Description	21.27(3.36)	21.07(3.36)	.627
		Act consciously	21.77(2.54)	21.77(3.54)	.622
		non-judgment	21.23(3.16)	21.03(3.16)	.548
		Not reacting	21.01(2.06)	20.81(3.06)	.427
		Total	107.3(2.02)	106.41(2.02)	.408
Mood Measurement Scale	National (n = 4)	Positive mood	22.42(5.33)	22.41(5.83)	.764
		Negative mood	23.22(15.0)	22.53(15.04)	.780
		Total	109.86(12.63)	109.33(11.63)	.889
	1st level (n = 6)	Positive mood	21.31(7.83)	21.21(8.83)	.550
		Negative mood	29.47(19.04)	29.07(15.04)	.609
		Total	108.16(21.63)	108.06(20.63)	.429
	2nd level (n = 10)	Positive mood	21.01(8.83)	21.01(4.43)	.337
		Negative mood	28.77(20.04)	28.77(21.04)	.350
		Total	105.26(22.63)	105.26(27.63)	.429
Contest Anxiety Questionnaire	National (n = 4)	Cognitive status anxiety	19.83(1.12)	19.73(1.12)	.345
		Anxiety about physical status	19.45(1.34)	19.55(1.34)	.237
		State self-confidence	24.84(1.55)	24.54(1.55)	.267
		Total	21.37(1.02)	21.27(1.55)	.117
	1st level (n = 6)	Cognitive status anxiety	22.15(1.12)	22.35(1.12)	.345
		Somatic state anxiety	22.23(1.34)	22.35(1.34)	.237
		State self-confidence	21.24(1.55)	21.44(1.55)	.267
		Total	21.87(1.42)	22.04(1.33)	.128
	2nd level (n = 10)	Cognitive status anxiety	24.33(1.12)	24.53(1.12)	.325
		Anxiety about physical status	24.25(1.34)	24.45(1.34)	.227
		State self-confidence	19.22(1.55)	19.27(1.55)	.227
		Total	22.6(1.33)	22.75(1.43)	.177
Trait Motor Self-Confidence Scale	National (n = 4)	Trait motor task confidence	21.63(4.18)	21.73(3.19)	.361
		Trait sports coping with self-confidence	33.73(5.52)	33.73(3.52)	.515
		Total	31.73(11.32)	31.73(12.32)	.401
	1st level (n = 6)	Trait motor task confidence	17.33(2.19)	17.23(2.39)	.361
		Trait sports coping with self-confidence	31.23(2.52)	31.33(2.32)	.615
		Total	29.23(2.32)	29.43(2.42)	.601
	2nd level (n = 10)	Trait motor task confidence	15.73(5.19)	14.73(5.19)	.515
		Trait sports coping with self-confidence	28.43(8.52)	28.43(8.52)	.401
		Total	22.53(12.32)	23.53(12.32)	.361

*Note. *p < .05, significant at .05.*

Table 4 Comparison of the outcome measurements of competitive Tai Chi athlete between levels

Variable	**Dimension**	**Mean (SD)** National (n = 8)	1st level (n = 12)	2nd level (n = 20)	***p* - value** National vs. 1st level	National vs. 2nd level	1st level vs. 2nd level
Five-Factor Mindfulness Questionnaire	Observe	23.38 (0.72)	22.98 (0.62)	21.88 (3.32)	.002**	.002**	.002**
	Description	22.45 (0.87)	22.02 (0.93)	21.17 (3.36)	.007**	.002**	.007**
	Act consciously	23.33 (0.94)	22.98 (0.93)	21.77 (2.54)	.008**	.002**	.002**
	Non-judgment	22.53 (0.77)	21.92 (0.87)	21.13 (3.16)	.002**	.002**	.080
	Not reacting	22.57 (0.06)	22.22 (0.06)	20.91 (2.56)	.002**	.002**	.002**
	Total	114.26 (0.08)	112.12 (0.05)	106.86 (2.33)	.002**	.002**	.002**
Mood Measurement Scale	Positive mood	22.42 (5.58)	21.26 (8.33)	21.01 (6.63)	.596	.153	.358
	Negative mood	22.88 (15.04)	24.27 (17.04)	28.77 (20.54)	.304	.002**	.454
	Total mood disturbance total score	109.60 (12.13)	108.11 (21.13)	105.26 (25.13)	.384	.051	.046*
Contest Anxiety Questionnaire	Cognitive status anxiety	19.78 (1.12)	22.25 (1.12)	24.43 (1.12)	.002**	.002**	.002**
	Somatic state anxiety	19.50 (1.34)	22.29 (1.34)	24.35 (1.34)	.002**	.002**	.002**
	State self-confidence	24.69 (1.55)	21.35 (1.55)	19.23 (1.55)	.002**	.002**	.002**
	Total	21.32 (1.05)	21.96(0.88)	22.67 (0.72)	.002**	.002**	.002**
Trait Motor Self-Confidence Scale	Trait motor task confidence	21.68 (3.69)	17.28 (2.13)	15.23 (5.18)	.002**	.002**	.002**
	Trait sports coping with self-confidence	33.73 (4.57)	31.28 (2.52)	28.43 (8.57)	.002**	.002**	.019*
	Total sports self-confidence score	21.73 (11.33)	29.33 (2.33)	22.53 (12.33)	.020*	.002**	.002**

*Note. *p < .05, significant at .05. ** p < .05, significant at .01.*

DISCUSSION

In the five-factor mindfulness questionnaire, the mood measurement scale, the contest anxiety questionnaire and trait motor self-confidence scale, the results showed that there was no significant difference in mindfulness level between genders and three levels of athletic Tai Chi athletes (Cai, 2023).

There were significant differences in the pre-match psychological characteristics of competitive Tai Chi athletes with different sports levels in the five-factor mindfulness questionnaire, mood measurement scale, contest anxiety questionnaire and trait motor self-confidence scale. In the five-factor mindfulness questionnaire, the national athletes were significantly better than the first and second level athletes in five dimensions and total scores and can maintain concentration and calm in the competition. However, due to the high training intensity and lack of experience, the observation ability of first and second level athletes was relatively weak (Zhao, 2022). There were also significant differences in the total score dimension among national, first and second level athletes (Qu et al., 2023). In the mood measurement scale, the negative emotions of national athletes were significantly lower than those of other athletes, indicating that the higher the sports level, the better the athletes can control the negative emotions in the competition. This kind of emotion control ability may come from their rich experience and psychological training in high-intensity competitions, while secondary athletes were more likely to have negative emotions under competition pressure due to lack of experience (Zhang, 2022). Generally speaking, high level athletes are higher than low level athletes. This may be related to the emphasis on psychological regulation and emotional management in Tai Chi training, so that athletes can maintain a relatively stable state of mind during the competition (Emily, 2022). The national athletes' cognitive state anxiety and physical state anxiety were significantly lower than those of the first and second level athletes, and their trait motor self-confidence scale were the highest. Because the first and second level athletes lack experience, they have more anxiety before the competition, which affects their performance (Baoyan, 2022). There were also significant differences in the total score dimension between national athletes and first and second level athletes (Li et al., 2022). The self-confidence level of national athletes was significantly higher than that of athletes of other levels, which may be related to their rich competition experience and strong psychological quality, which enables them to maintain self-confidence and calm in the face of complex competition situations (Bu, 2022).

CONCLUSIONS

This study revealed the significant differences in the five-factor mindfulness questionnaire mood measurement scale contest anxiety questionnaire and trait motor self-confidence scale among competitive Tai Chi athletes of different sports levels. National level athletes, with their rich experience and high-intensity psychological training, perform well in these dimensions, while first and second level athletes perform poorly in some dimensions. There was no significant difference between male and female competitive Tai Chi athletes. These findings provide an important reference for the research of sports psychology and provide a basis for the intervention measures to improve the psychological quality of athletes. For athletes of different competitive levels, the development of personalized psychological training programs, especially mindfulness training, may help to improve their psychological state and self-confidence, and then improve their competitive performance.

AUTHOR CONTRIBUTIONS

All authors contributed significantly to the final version of this manuscript and to the interpretation of the results. Study design: Ruiting Su and Dr.Wannaporn Sumranpat Brady. Data collection: Ruiting Su. Statistical analysis: Ruiting Su. Data interpretation: Ruiting Su and Dr.Wannaporn Sumranpat Brady. Literature search: Ruiting Su. Writing original draft preparation: Ruiting Su. Writing review and editing: All authors. Supervision: Dr.Wannaporn Sumranpat Brady. Project administration: Dr.Wannaporn Sumranpat Brady. All authors have read and agreed to the published version of the manuscript.

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ORIGINAL ARTICLE

The influence of menstrual cycle in heart rate variability and performance: A case study of a highly-trained female long-distance runner

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ABSTRACT

Introduction: Heart rate variability (HRV) is a non-invasive marker of the autonomic nervous system (ANS) that provides insights into physiological responses to training. This study investigates the relationship between HRV and athletic performance with and without the menstrual cycle (MC) in a highly-trained female long-distance runner. Methods: A 24-year-old elite female long-distance runner participated in this quantitative case study. HRV was recorded daily using a Polar H10 chest strap over three months, both with and without the MC. Athletic performance was assessed through mean power output (MPO) during 3-minute time trials (TT) using a Stryd inertial sensor. Four evaluations were conducted: two without MC and two with MC. Results: A nearly perfect correlation was found between HRV (rolling RMSSD) and MPO during the first TT without MC (r = 0.969, $p \leq .001$). However, no significant correlations were observed during the second TT with MC, the third TT without MC, or the fourth TT with MC. These findings suggest that HRV is a reliable marker for predicting athletic performance in the absence of MC but is influenced by hormonal fluctuations during the MC. Conclusion: HRV monitoring is a valuable tool for assessing internal load and predicting performance in female athletes. However, its reliability can be affected by the menstrual cycle and by accumulated fatigue. Future research should explore larger sample sizes and the impact of contraceptives on HRV and performance.
Keywords: Performance analysis, Athletic performance, Autonomic nervous system, Menstrual cycle, Inertial sensor.

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INTRODUCTION

Heart rate variability (HRV) is defined as the variation in time between each heartbeat (RR interval) and is calculated by analysing the distance in milliseconds between each RR interval of the QRS complex of a normal electrocardiogram that occurs when the ventricles depolarize (Hunt & Saengsuwan, 2018; Poehling & Llewellyn, 2019). HRV is the result of interactions between the autonomic nervous system (ANS) and the cardiovascular system. Therefore, its analysis provides a non-invasive method for studying ANS activity, which is particularly valuable in sports medicine (Campos et al., 2021; Kiss et al., 2016). The ANS functions to ensure that the physiological integrity of cells, tissues and organs throughout the body is maintained (homeostasis) and to execute adaptive responses to changes in the external and internal environment (Plews et al., 2017; Tsuji et al., 1996). The ANS is made up of two subsystems: the sympathetic nervous system (SNS), which allows the body to respond to survival challenges (fight or flight), states of anxiety, stress and physical exercise, while the second is the parasympathetic nervous system (PNS), known for its participation in energy conservation and restoration processes by causing a reduction in heart rate and blood pressure, facilitating the digestion and absorption of nutrients and the elimination of waste (Carrasco-Poyatos et al., 2020; Hunt & Saengsuwan., 2018).

Among the ANS stressors is sports training: the systematic process of exercising (stimuli) for the development of physical qualities or sports skills (Buchheit et al., 2010; Campos et al., 2021). When the stimulus are appropriate, an adaptive physiological and psychological response is generated that is unique to each individual (Campos et al., 2021; Düking et al., 2020). In endurance sports, this adaptive response to sports training can be quantified using external load methods such as real-time speed and mean power output (MPO) measurement with inertial sensors (e.g., potentiometers such as "*Stryd*") (Ruiz-Alias et al., 2023). While subjective methods such as the widely used rating of perceived exertion (RPE), retrospective questionnaires, direct observation diaries, and internal load methods such as monitoring of physiological parameters based on the measurement of oxygen consumption, blood lactate concentration and HRV can also be used (Abbiss & Laursen., 2008; Coyle et al., 1991). The HRV monitoring has gained relevance in the last decade to control stress and training adaptations, as well as detecting overtraining (Imbach et al., 2020; Perez-Gaido et al., 2021). A systematic review on HRV-guided training in long-distance runners found significant improvements in physical performance in HRV-guided groups compared to those following a conventional training plan (da Silva et al., 2019). However, the benefits of HRV-guided training for athletes' physical performance according to their biological sex, particularly for females during the menstrual cycle (MC), need further study.

Indeed, De Jonge (2003) observed that responses to exercise can vary depending on the stage of the MC, i.e. follicular phase (the first day of the cycle coincides with the beginning of menstruation and marks the beginning of this phase) versus luteal phase (begins after ovulation) (Aguilar-Macías & Ruiz-Sánchez, 2018; Dokumacı & Hazır, 2019). In the follicular phase, the release of follicle-stimulating hormone and luteinizing hormone is stimulated, favouring low concentrations of progesterone (PG) and the production of oestrogen (EG) (De Jonge et al., 2003). In the luteal phase, the concentrations of EG and PG tend to increase, thus one of the effects of PG is the increase in pulmonary ventilation, as well as the loss of water and sodium, reducing plasma volume during the post-ovulatory phase (Dokumacı & Hazır, 2019). A meta-analysis reported decreased cardiac vagal activity from the follicular to the luteal phase in females with regular MC (Dokumacı & Hazır, 2019). In agreement with this, MC phase comparisons revealed lower HRV in the mid-luteal phase (characterized by elevated PG) than in other phases (De Jonge et al., 2003). No significant main or interactive effects of EG on HRV were found (Aguilar-Macías & Ruiz-Sánchez., 2018). According to the scientific literature, the benefits of HRV in sports training are known, but its manifestation during the MC and its relationship with athletic performance in women is still unclear. Therefore, the present study aims to investigate the relationship between HRV and athletic performance in a female long-distance runner, both with and without MC. Based on the reviewed literature (Boullosa et al,. 2021; Brar et al,. 2015; Kokts-Porietis et al,. 2019), we hypothesized that HRV is directly correlated with athletic performance both with and without MC.

MATERIALS AND METHODS

Participant

A high-level female Chilean long-distance runner (age = 24 years; height = 164 cm; weight = 51.3 kg; training experience >4 years; weekly training volume = 130 ± 15 km) voluntarily agreed to participate in the present study. At the time of the measurements, she was training seven days per week and consistently completed the 10,000 meters in under 40 minutes. The participant, an elite athlete specializing in the 10,000-meter event, had achieved significant milestones, including a runner-up position in her inaugural adult competition and earning a spot on the national team. Furthermore, she held a record of titles in regional championships across multiple age groups and distances. At the start of the study, she was free of any illness or musculoskeletal injuries that could impact her athletic performance. This study was conducted in accordance with the principles stated in the Declaration of Helsinki and received approval from the Universidad de Los Lagos Ethics Committee under the code 0104-024.

Experimental procedure

The procedure was divided into three stages:

Stage 1: The athlete was informed about the study procedures and provided with an informed consent form containing all relevant details of the research. She was given a maximum of seven days to review the document and confirm her participation by signing the consent form.

Stage 2: Upon agreeing to participate, the evaluation period began. Anthropometric measurements were taken, including height, measured using a stadiometer (Seca 206; Seca Ltd, Hamburg, Germany), and body mass, assessed with a digital scale (Seca 813; Seca Ltd, Hamburg, Germany). The Rate of Perceived Exertion (RPE) was assessed using the 0-10 scale (Foster et al., 2001). Heart rate variability (HRV) was recorded daily for three months. Measurements involved placing a chest strap (Polar H10, Polar Electro Oy, Kempele, Finland) at chest level and recording data for three minutes in a supine position. HRV parameters, including the root mean square of successive differences in RR intervals over the last seven days (rollingRMSSD), heart rate (HR), and RR intervals over the last seven days (rollingRR), were recorded using the 'Elite HRV' smartphone application (Perrotta et al., 2017) each morning upon waking. The collected data were exported from the application and processed using a medium-threshold beats correction filter in Kubios software (v.3.0.0, HRV analysis, University of Eastern Finland) (Tarvainen et al., 2014). During this period, the athlete continued her usual training program without any modifications.

Stage 3: Performance metrics were recorded using an inertial sensor (Stryd Summit Power Meter, Boulder, CO, USA) attached to the laces of the athlete’s right shoe. The sensor captured metrics such as mean power output (MPO), speed, and distance travelled. A standardized warm-up was performed before the time trial (TT), consisting of 10 minutes of low to moderate-intensity jogging on a treadmill, followed by three 30-second accelerations to maximum speed based on the athlete's level. After completing the warm-up, the athlete performed a 3-minute maximal effort time trial under identical environmental and temperature conditions (Sousa et al., 2022). This test was repeated four times.

The first and third evaluations were conducted during the non-menstrual phase (without MC), while the second and fourth evaluations took place during the follicular phase of the MC (with MC). A 4-day interval separated the first and second assessments, followed by a one-month interval between the second and third assessments, and another 4-day interval between the third and fourth assessments (Düking et al., 2020). The 'Flo' menstrual calendar smartphone application (Grieger et al., 2020) was used to monitor the MC and identify the follicular phase. Following the fourth 3-minute assessment, the collected data were analysed.

Statistical analysis

The Shapiro-Wilk test was used to confirm the normal distribution of the data (p > .05). The relationship between HRV (rolling RMSSD) and athletic performance (TT/with and without MC) was assessed using the Pearson correlation coefficient (r) and the standard error of estimate (SEE) obtained from linear regression analysis. The strength of the r coefficient was interpreted as: trivial (0.00-0.09), small (0.10-0.29), moderate (0.30-0.49), large (0.50-0.69), very large (0.70-0.89), nearly perfect (0.90-0.99), and perfect (1.00) (Hopkins et al., 2009). A rolling RMSSD and TT/With and Without MC relationship was considered acceptable if the following criteria were met: nearly perfect r (>0.90), low SEE (absolute ≤ 0.65; relative ≤ 0.02), and statistical significance of p ≤ .05. Statistical analyses were performed using the SPSS software package (IBM SPSS version 25.0, Chicago, IL, USA).

Table 1. Descriptive statistics for 3-minute time trial (TT) performance and heart rate variability (HRV) metrics.

	1 TT/Without MC	2 TT/With MC	3 TT/ Without MC	4 TT/ With MC
Heart rate (bpm)	46	49	61	62
RR (ms)	1312.2	1234	1110.23	1211.89
Rolling RR (ms)	1315.25 ± 21	1278.83 ± 12.3	1346.34 ± 69.8	1270.29 ± 15.1
RMSSD (ms)	62.04	71.98	88.08	97.22
Rolling RMSSD (ms)	69.15 ± 6.66	62.79 ± 1.68	124.77 ± 22.6	120.36 ± 5.75
Distance (m)	761	755	708	767
Rhythm (km/h)	14.61 ± 0.47	14.46 ± 0.47	13.54 ± 0.86	14.70 ± 0.86
Relative power (W/kg)	4.24 ± 0.11	4.21 ± 0.12	3.95 ± 0.23	4.30 ± 0.22
Absolute MPO (W)	220.6 ± 5.82	218.77 ± 6.15	205.6 ± 12.14	223.11 ± 11.64
Relative MPO (W/kg)	4.24 ± 0.11	4.21 ± 0.12	3.95 ± 0.23	4.30 ± 0.22

Note. MC: Menstrual cycle; MPO: Mean power output; RMSSD: Root mean square of the RR intervals; Rolling: average accumulation of data (RR or RMSSD) of the last 7 days; bpm: beats per minute; TT: time trial (3-min).

RESULTS

A strong positive correlation was observed between the first evaluation of TT/without MC and the rolling RMSSD in absolute and relative values of MPO (r ≥ 0.969 and 0.962; p ≤ .001 and .002; SEE ≤ 0.62 and 0.01 Table 2). For the TT/without MC and the rolling RR of this first evaluation the relationship criteria were not met (Table 2).

The second evaluation did not meet the relationship criteria between TT/with MC and the rollingRMSSD in absolute and relative values of MPO.

The third evaluation showed no relationship between TT/without MC and the rollingRMSSD as well as the rollingRR in absolute and relative values of MPO (Table 2).

The fourth assessment showed no relationship between TT/ with MC and rollingRMSSD as well as rollingRR in absolute and relative values of MPO (Table 2).

Table 2. Relationship between HRV and sports performance (MPO).

	VFC	Power	Pearson *r*	*p*-value	R^2	SEE
1 TT/Without CM	Rolling RR (ms)	Absolute MPO (W)	0.92**	.009*	.847(+)	0.98
		Relative MPO (W/kg)	0.93**	.007*	.864(+)	0.01
	Rolling RMSSD (m/s)	Absolute MPO (W)	0.969**	.001*	.939(+)	0.62
		Relative MPO (W/kg)	0.962**	.002*	.926(+)	0.01
2 TT/With CM	Rolling RR (ms)	Absolute MPO (W)	0.093	.881	.009	-0.32
		Relative MPO (W/kg)	0.093	.881	.009	0.01
	Rolling RMSSD (m/s)	Absolute MPO (W)	0.598	.287	.357	0.77
		Relative MPO (W/kg)	0.598	.287	.357	0.01
3 TT/Without CM	Rolling RR (ms)	Absolute MPO (W)	-0.629	.001*	.396	2.7
		Relative MPO (W/kg)	-0.624	.01*	.389	0.05
	Rolling RMSSD (m/s)	Absolute MPO (W)	0.446	.029*	.162	0.05
		Relative MPO (W/kg)	0.458	.024*	.21	0.05
4 TT/with CM	Rolling RR (ms)	Absolute MPO (W)	-0.649	.236	.421	0.96
		Relative MPO (W/kg)	-0.649	.236	.421	0.01
	Rolling RMSSD (m/s)	Absolute MPO (W)	-0.237	.701	.056	1.22
		Relative MPO (W/kg)	-0.237	.701	.056	0.02

*Note. HRV: Heart Rate Variability; MC: Menstrual Cycle; R^2: Coefficient of determination; RMSSD: Root Mean Square of Successive Differences of RR intervals; SEE: Standard error of the estimate; TT: Time Trial; (+): Strong predictive power; **: Near-perfect correlation; *: Significance level of .01.*

DISCUSSION

This study aimed to explore the relationship between HRV and athletic performance (i.e.TT) in a highly-trained female long-distance runner, both with and without the influence of the MC. The findings revealed a positive correlation between HRV and athletic performance without the MC, represented by the 3-minute TT, through the MPO (r > 0.9), while this relationship is modified when the 3-minute TT is with the MC because the relationship shown is not significant (r < 0.90; *p* > .05). Additionally, HRV was found to be influenced by hormonal fluctuations during the MC and by cumulative training loads, expressed as kilometres run.

The first evaluation ("*1 TT/without MC*") demonstrated an almost perfect positive correlation between rollingRMSSD and both absolute and relative MPO values (r = 0.969 and 0.962; *p* = .001 and .002; SEE = 0.62 and 0.01). This suggests that increased HRV corresponds to improved athletic performance in the 3-minute TT. Similar findings were reported by D'Ascenzi et al. (2014), who examined elite female volleyball players and identified a relationship between HRV parameters and performance indicators for technical skills influenced by pre-competitive stress, such as serving and receiving. They concluded that autonomic nervous system activity plays a critical role in sport-specific performance, with heightened sympathetic activity being associated with fewer successful receptions. Consistently, higher rollingRMSSD values before competition were linked to improved performance.

In contrast to the first evaluation, the second evaluation ("*2 TT/with MC*") revealed no significant relationship between rollingRMSSD and athletic performance (i.e., MPO in the 3-minute TT). This aligns with previous studies (Pestana, 2014; Kokts-Porietis, 2019) that also found no correlation between HRV during the MC and athletic performance in women. Additionally, other research highlights increased sympathetic nervous system (SNS) activity and decreased parasympathetic nervous system (PNS) activity during the follicular and luteal phases of the MC (Dokumacı & Hazır, 2019). These findings suggest that hormonal changes associated with the MC may significantly affect athletic performance in women.

The third evaluation, conducted without the MC ("*3 TT/without MC*"), revealed significant differences when compared to the first evaluation (i.e., "*1 TT/without MC*"), with a lack of correlation between HRV and TT performance (r = 0.44; *p* = .02). This discrepancy may result from accumulated fatigue during the training period preceding the competition and assessment, as noted in earlier studies (Schmitt et al., 2013; Halson et al., 2014).

Similarly, the fourth evaluation ("*4 TT/with MC*") showed no relationship between rollingRMSSD and performance, consistent with the findings from the second evaluation. This could be attributed to the combined effects of fatigue accumulation and hormonal changes during the MC (Schmitt et al., 2013; Halson et al., 2014).

Finally, these findings should be interpreted within the context of the study's limitations. One limitation is the high-performance level of the participant, which may limit generalizability to other populations. Additionally, the short evaluation period (three months) restricts broader conclusions. Nevertheless, this study provides valuable insights and a foundation for future research on the influence of the menstrual cycle on HRV and athletic performance.

Practical applications and future directions

HRV-guided training allows coaches to assess training and physiological readiness of the athletes prior to the different phases of the MC and thus control and/or adapt training loads with the aim of achieving greater performance. Therefore, HRV can be considered a reliable and valuable tool for optimizing the sports performance of both novice and trained female athletes and thus reduce physiological stress, considering one of the most important female biological processes, the MC. Therefore, taking into account the aforementioned limitations, the results serve as a basis for future research.

Future investigations should aim to increase sample size and explore the association between the effects of contraceptives used by athletes and their implication on sports performance and thus determine its impact on HRV-guided and monitored athletic performance.

CONCLUSION

The quantification of HRV in the time domain provides information regarding internal load in highly trained athletes. However, individual characteristics such as the athletic level and the MC phase could influence these measures. Therefore, our results highlight the potential role of HRV as a monitoring tool for athletes and coaches to better dose training loads and improve performance across the MC.

AUTHOR CONTRIBUTIONS

Conceptualization: F.B.-M., J.A.-G., A.Ñ.-A.; methodology: F.B.-M., J.A.-G., A.Ñ.-A.; software: A.Ñ.-A.; validation: F.B.-M., J.A.-G., A.Ñ.-A.; formal analysis: F.B.-M., J.A.-G., A.Ñ.-A.; investigation: F.B.-M., J.A.-G., A.Ñ.-A., L.Ñ.-A., E.G.-C., V.C.-U., M.C.-B.; resources: F.B.-M., J.A.-G., A.Ñ.-A., L.Ñ.-A., E.G.-C., V.C.-U., M.C.-B.; data curation: F.B.-M., J.A.-G., A.Ñ.-A., L.Ñ.-A., E.G.-C., V.C.-U., M.C.-B.; writing—original draft preparation: F.B.-M., J.A.-G., A.Ñ.-A., L.Ñ.-A., E.G.-C., V.C.-U., M.C.-B.; writing—review and editing: F.B.-M., J.A.-G., A.Ñ.-A., L.Ñ.-A., E.G.-C., V.C.-U., M.C.-B.; visualization: F.B.-M., J.A.-G., A.Ñ.-A., L.Ñ.-A., E.G.-C., V.C.-U., M.C.-B.; supervision: F.B.-M., J.A.-G., A.Ñ.-A., L.Ñ.-A., E.G.-C., V.C.-U., M.C.-B. All authors have read and approved the final version of the manuscript.

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No potential conflict of interest was reported by the authors.

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