REVIEW ARTICLE

Punching performance, physiological responses and lower-limb neuromuscular characteristics in boxing: A systematic review

Giuseppe Penna . *Faculty of Kinesiology. University of Split. Split, Croatia.*
Igor Jelaska. *Faculty of Kinesiology. University of Split. Split, Croatia.*
Gaetano Altavilla. *Department of Education Sciences and Sport. Pegaso Online University. Naples, Italy.*

ABSTRACT

Introduction: Boxing is a high-intensity intermittent sport in which performance depends on the ability to produce effective punches and sustain their intensity during repeated efforts. Punching performance, physiological responses, and lower-limb neuromuscular characteristics are key factors in understanding boxing-specific performance; however, current evidence remains fragmented. Objective: To systematically analyse the literature on punching performance, physiological responses, and lower-limb neuromuscular characteristics in boxing, and to examine the relationships between these variables. Methods: The review followed PRISMA 2020 guidelines and was structured according to the PICOS model. Literature searches were conducted in PubMed and Google Scholar for studies published between January 2010 and January 2026. After screening titles, abstracts, and full texts, 46 studies were included in the qualitative synthesis. Results: A high methodological heterogeneity was observed across study designs, samples, protocols, measurement tools, and outcomes. Punching performance was the most investigated domain, while physiological responses mainly included heart rate, oxygen uptake, blood lactate, and perceived exertion. Lower-limb neuromuscular characteristics were less explored, and no study directly assessed muscle–tendon stiffness. Conclusions: Current evidence remains fragmented and future studies should adopt integrated approaches to improve performance assessment and training prescription in boxing.
Keywords: sports performance; punch impact; heart rate; oxygen uptake; muscle–tendon stiffness; explosive strength.

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Corresponding author. *Faculty of Kinesiology. University of Split. Teslina 6. 21 000 Split, Croatia.*
E-mail: giuseppe.penna85@gmail.com
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INTRODUCTION

Boxing is a combat sport in which performance depends on the interaction of technical, tactical, and physical components (Ceruso et al., 2019), as well as on the ability to execute effective offensive and defensive actions during a bout (Chaabène et al., 2015; Slimani et al., 2017). In this context, competitive success is closely associated with the ability to sustain high match intensity, as in many other sports (Di Lascio et al., 2026; D'Isanto et al., 2022), and to repeatedly produce fast and powerful punches throughout the entire duration of the contest (Chaabène et al., 2015; Finlay et al., 2023; Wilson et al., 2020). The literature also describes boxing as a high-intensity intermittent sport characterised by alternating explosive actions and short, often incomplete, recovery periods (Franchini, 2020; Slimani et al., 2017; Thomson & Lamb, 2017b). Studies conducted during boxing-specific protocols have highlighted high physical and technical demands, with repeated high-intensity offensive and defensive actions across all rounds of competition (Finlay et al., 2018; Thomson & Lamb, 2017a, 2017b; Xu et al., 2025).

Within this performance model, increasing attention has been directed towards the assessment of indicators of punching performance (Lenetsky et al., 2013; Loturco et al., 2016). Variables such as punch impact force, punch velocity, and punch power, as well as additional parameters derived from measurement devices, have been used to objectively describe the athlete's ability to produce potentially more effective strikes in performance terms (Dunn et al., 2022; Lenetsky et al., 2013; Pinto et al., 2025). Several studies suggest that higher-level boxers tend to produce greater mechanical output during punching, confirming the relevance of indicators of punching performance in the evaluation of boxing performance (Loturco et al., 2016; Pinto et al., 2025). However, the available literature shows marked methodological heterogeneity, as indicators of punching performance has been assessed through maximal single-punch tests, repeated or continuous boxing-specific punching protocols—including simulated bouts, sparring, pad work, and heavy-bag training—as well as protocols structured in rounds or with an intermittent work organisation, and boxing-specific incremental tests, using different tools such as force platforms, instrumented targets, dummies, sensor-equipped punching bags, or systems based on accelerometers and inertial sensors (Finlay et al., 2018; Liu et al., 2022; Venckunas et al., 2022; Xu et al., 2025). This variability limits direct comparability between studies and makes a unified synthesis of the available evidence difficult.

In parallel, boxing imposes a high physiological load (Franchini, 2020; Slimani et al., 2017). Numerous studies have reported elevated values of heart rate, oxygen uptake, and blood lactate concentration during simulated bouts and sport-specific training, highlighting substantial physiological demands sustained over time (Arseneau et al., 2011; de Lira et al., 2013; El-Ashker et al., 2018; Ghosh, 2010; Venckunas et al., 2022). It has also been observed that the magnitude of physiological responses varies according to exercise intensity, suggesting a relationship between physiological load and sport-specific performance in boxing (Finlay et al., 2018; Thomson and Lamb, 2017b; Usher and Babraj, 2024). Nevertheless, studies that jointly examine indicators of punching performance and physiological responses during boxing-specific protocols remain limited, resulting in only partial understanding of the interactions between internal load and performance output.

A further area of interest concerns lower-limb neuromuscular characteristics. Although boxing is frequently associated with the upper limbs, available evidence indicates that punching effectiveness depends on the coordinated involvement of the whole body and on the ability to generate force from the ground up (Lenetsky et al., 2015; Stanley et al., 2018). In particular, lower-limb explosive strength parameters such as jump height, force, power, rate of force development (RFD), and ground reaction force (GRF) have been associated in some studies with indicators of punching performance (Chottidao et al., 2022; Dunn et al., 2022; Loturco et al., 2016; Loturco et al., 2021). In parallel, growing attention has been directed towards lower-limb muscle-tendon stiffness, a property of the muscle-tendon unit associated with the ability to optimise force production during dynamic and explosive actions (Brazier et al., 2019; Wdowski et al., 2023). However, in boxing the available evidence remains limited, and no studies have directly examined lower-limb muscle-tendon stiffness in relation to punching performance (Chottidao et al., 2022).

Overall, the literature appears fragmented: indicators of punching performance represent the most extensively investigated domain, whereas physiological responses and lower-limb neuromuscular characteristics have often been studied separately, with limited integration with indicators of punching performance. This limits a comprehensive understanding of the main components of boxing performance and their possible interactions.

From a broader theoretical perspective, boxing performance may be interpreted as the result of the dynamic interaction between mechanical output during punching, physiological load, and lower-limb neuromuscular characteristics. This perspective suggests that the ability to produce high levels of punching performance does not depend exclusively on the technical characteristics of the movement, but also on the integration between physiological responses and lower-limb neuromuscular characteristics involved in the production and maintenance of performance. In this context, a multidimensional interpretation of boxing performance could contribute to a deeper understanding of the relationships between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics involved in the production and maintenance of performance during intermittent high-intensity efforts (Franchini, 2020; Loturco et al., 2016; Venckunas et al., 2022).

In light of these considerations, the present systematic review aims to analyse the available evidence regarding indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics in boxing, as well as to examine the potential relationships between these domains. The aim is to identify methodological convergences, major knowledge gaps, and future research perspectives. Furthermore, the integration of these domains could support the development of more comprehensive methodological models for the analysis of boxing performance, contributing to the definition of a more comprehensive theoretical framework applicable to future research, with potential applications in athlete assessment, monitoring, and training prescription.

MATERIAL AND METHODS

Study design and reporting guidelines

The present review was conducted as a systematic review with qualitative synthesis, in accordance with the PRISMA 2020 guidelines (Page et al., 2021), and the research question was structured according to the PICOS model (Population, Intervention/Exposure, Comparator, Outcomes, and Study design). Considering the heterogeneity of study designs, experimental protocols, and variables reported in the included studies, no meta-analysis was performed.

Information sources and search strategy

The literature search was conducted using the PubMed and Google Scholar databases, limiting the time frame to publications between January 2010 and January 2026. For PubMed, the search was performed using combinations of keywords relevant to the aims of the review, combined through Boolean operators (AND, OR) and the resulting records were exported. For Google Scholar, the search was conducted using keyword combinations consistent with the same aims; for each combination, the first 100 results were screened, and records considered relevant were exported. Overall, 327 records were identified.

Research question and PICOS model

The research question was defined a priori according to the PICOS model.

Population

Boxers, with no restrictions regarding sex, competitive level, or age, provided they were active participants in training or competitive settings.

Intervention/Exposure

Exposure to different types of punching protocols, classified as: (i) maximal single-punch tests; (ii) repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, heavy-bag training, as well as protocols structured in rounds or with an intermittent exercise format; (iii) boxing-specific incremental tests.

Comparator

Between-group comparisons and/or within-subject comparisons across experimental conditions.

Outcomes

(i) indicators of punching performance; (ii) physiological responses; (iii) lower-limb neuromuscular characteristics.

Study design

Observational and experimental studies reporting original data, including cross-sectional, pre–post, repeated-measures, and case-study designs.

Eligibility criteria

Studies were considered eligible if they met the following criteria:

(i) *Population*: Boxers, with no restrictions regarding sex, competitive level, or age, provided they were active participants in training or competitive settings.
(ii) *Study design*: Observational and experimental studies reporting original data, including cross-sectional, pre–post, repeated-measures, and case-study designs.
(iii) *Outcomes*: Indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics.
(iv) *Protocols*: Use of valid protocols classified as: maximal single-punch tests; repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, heavy-bag training, as well as protocols structured in rounds or with an intermittent exercise format; and boxing-specific incremental tests.

Studies were excluded if the full-text was unavailable, if they reported non-boxing-specific outcomes, if outcomes were not relevant to the aims of the review, or if they did not provide original data (e.g., reviews, editorials, or conference abstracts).

Study selection

All identified records were imported into reference management software (Zotero, Corporation for Digital Scholarship, Vienna, VA, USA), within which duplicates were identified and removed prior to the screening phase.

A total of 327 records were initially identified. After duplicate removal (n = 174), 153 records underwent title and abstract screening. At this stage, 78 articles were excluded.

Subsequently, 75 articles were assessed in full-text to determine eligibility. Of these, 46 studies were included in the final qualitative synthesis, whereas 29 were excluded for the following reasons: full-text unavailable (n = 15), non-boxing-specific outcomes (n = 10), and outcomes not relevant to the aims of the review (n = 4).

The study selection process is summarised in the PRISMA 2020 flow diagram (Figure 1).

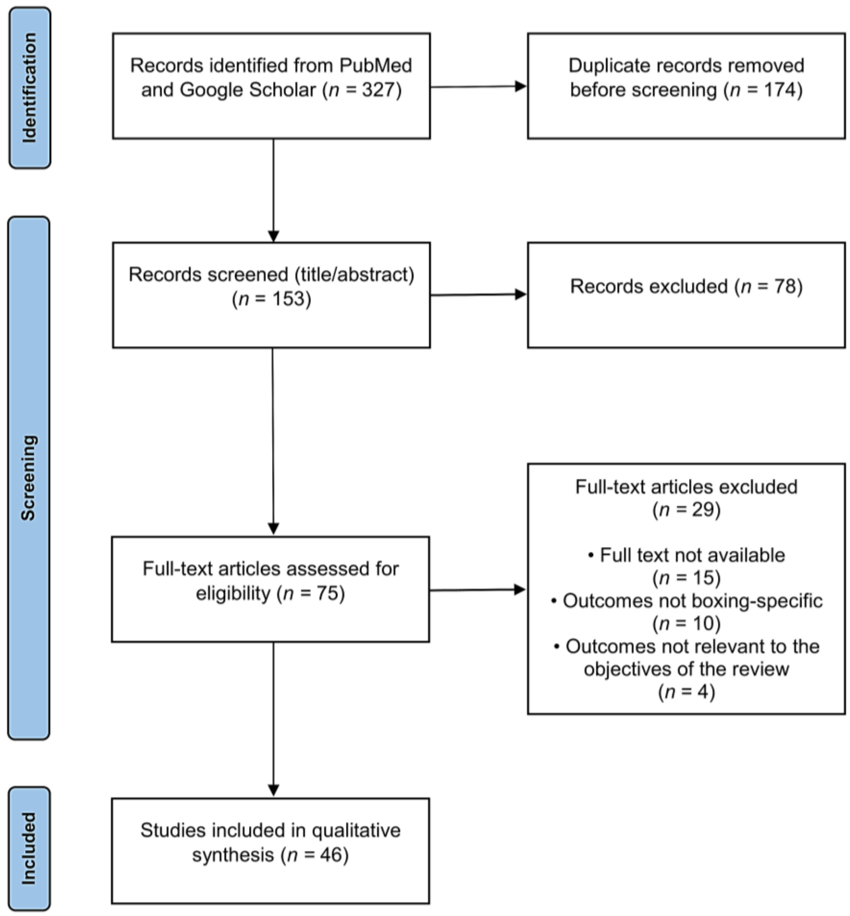

Figure 1. PRISMA 2020 flow diagram of the study selection process.

Data extraction

Data extraction was conducted systematically for all included studies. For each article, the following information was collected:

(i) General study characteristics (authors, year of publication, study design, and setting);
(ii) Sample characteristics (sample size, sex, competitive level, age, and sporting experience, where reported);
(iii) Description of the protocols used (type, structure, and applied context);
(iv) Indicators of punching performance;
(v) Physiological responses;
(vi) Lower-limb neuromuscular characteristics.

Qualitative synthesis
Given the methodological heterogeneity of the included studies, the synthesis of results was conducted using a structured qualitative approach.

Studies were analysed descriptively, with particular attention to sample characteristics, protocols adopted, indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics.

The synthesis was organised according to a systematic framework aimed at identifying convergences, divergences, and gaps within the literature, while ensuring internal consistency and traceability of the evidence supporting the identification of research gaps.

RESULTS

Study selection process
The study selection process is illustrated in Figure 1. Overall, 327 records were identified through searches of the PubMed and Google Scholar databases. After duplicate removal (n = 174), 153 records underwent title and abstract screening, resulting in the exclusion of 78 non-relevant studies.

Subsequently, 75 articles were assessed in full-text to determine eligibility. Of these, 29 studies were excluded for the following reasons: full-text unavailable (n = 15), non-boxing-specific outcomes (n = 10), and outcomes not relevant to the aims of the review (n = 4).

At the end of the selection process, a total of 46 studies were included in the qualitative synthesis of the present systematic review.

Study characteristics
The main characteristics of the included studies (n = 46) are summarised in Table 1. Overall, the included studies were published between 2010 and 2025 and involved boxers of different sex, competitive level, and age categories, with a predominance of male amateur and elite samples.

The most frequently represented study designs were observational, predominantly cross-sectional, and experimental, including pre–post and repeated-measures designs. The protocols employed mainly comprised maximal single-punch tests, repeated or continuous boxing-specific punching protocols, and boxing-specific incremental tests. In some studies, these protocols were incorporated into training interventions or experimental conditions aimed at evaluating acute or chronic adaptations in boxing-specific performance.

The outcomes analysed primarily concerned indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics.

DISCUSSION

Descriptive synthesis
Overall, the findings highlight marked heterogeneity among the included studies in terms of study designs, sample characteristics, experimental protocols, measurement tools, and outcomes analysed. This variability reflects a methodological landscape that remains fragmented and limits direct comparison of the available findings.

Table 1. Characteristics of the included studies (n = 46).

Study (First author, year)	Study design	Sample (n)	Sex	Competitive level
Ghosh, 2010	Repeated-measures	6	Male	Elite
Arseneau et al., 2011	Cross-sectional	9	Male	Amateur
de Lira et al., 2013	Cross-sectional	10	Male – Female	Highly trained
Loturco et al., 2016	Cross-sectional	15	Male – Female	Elite
Cunniffe et al., 2017	Repeated-measures	6	Male	Elite
Hukkanen and Häkkinen, 2017	Repeated-measures	7	Male	National
Thomson and Lamb, 2017a	Experimental	28	Male	Amateur
Thomson and Lamb, 2017b	Experimental	28	Male	Amateur
El-Ashker et al., 2018	Repeated-measures	11	Male	Elite
Finlay et al., 2018	Experimental	9	Male	Elite
Kamandulis et al., 2018	Experimental	18	Male	Experienced amateur
Kim et al., 2018	Experimental	15	Male	Elite
Lenetsky et al., 2018	Cross-sectional	20	Male	Trained vs untrained
Finlay et al., 2020	Experimental	14	Male	Elite
Herrera-Valenzuela et al., 2021	Experimental	16	Male	National
Loturco et al., 2021	Experimental	8	Male	Elite
Brown et al., 2022	Cross-sectional	22	Male	Amateur
Bu, 2022	Experimental	20	Female	Elite
Chottidao et al., 2022	Experimental	24	Male	Junior amateur
Dunn et al., 2022	Cross-sectional	28	Male	Highly trained
Finlay et al., 2022	Experimental	10	Male	Elite
Liu et al., 2022	Cross-sectional	16	Male	Elite and junior
Venckunas et al., 2022	Cross-sectional	11	Male	High-level amateur
Chwała et al., 2023	Cross-sectional	18	Male	Competitive
Maciel et al., 2023	Cross-sectional	12	Male – Female	Amateur
Merlo et al., 2023	Cross-sectional	227	Male – Female	Amateur
Cui et al., 2024a	Experimental	24	Female	Elite
Cui et al., 2024b	Experimental	24	Male	Elite
de Oliveira et al., 2024	Cross-sectional	10	Male	Competitive
Finlay et al., 2024	Experimental	10	Male	Elite
Liu et al., 2024	Experimental	24	Female	Elite
Mosler et al., 2024a	Cross-sectional	13	Male	Advanced
Mosler et al., 2024b	Cross-sectional	13	Male	Advanced
Niu et al., 2024	Experimental	37	Female	Elite
Usher and Babraj, 2024	Cross-sectional	10	Male	Professional
Venckunas et al., 2024	Cross-sectional	12	Male	Elite
Wu et al., 2024	Cross-sectional	174	Male	Elite
Finlay, 2025	Case study	3	Male	Elite
Jin et al., 2025	Experimental	18	Male	Amateur
Kacprzak et al., 2025	Cross-sectional	30	Male	Trained
Liu et al., 2025	Experimental	29	Male	Elite
Pinto et al., 2025	Cross-sectional	69	Male	Practitioners
Sánchez-Ramírez et al., 2025	Experimental	29	Male	Amateur
Singh et al., 2025	Experimental	30	Male	Adolescents
Söyler et al., 2025	Experimental	20	Male	National
Xu et al., 2025	Experimental	36	Male	Amateur

The literature is characterised by the coexistence of observational studies, predominantly cross-sectional in design (Arseneau et al., 2011; Dunn et al., 2022; Lenetsky et al., 2018), experimental studies (Finlay et al., 2020; Liu et al., 2024; Thomson and Lamb, 2017a, 2017b), and a limited number of case studies (Finlay, 2025).

Samples were heterogeneous with regard to sex, competitive level, and age, with a clear predominance of male amateur and elite boxers and more limited representation of female athletes or mixed samples (Bu, 2022; Cui et al., 2024a, 2024b; Maciel et al., 2023; Merlo et al., 2023). This distribution reduces the generalisability of the available evidence to the wider boxing population.

Substantial differences were also observed in the protocols adopted, including maximal single-punch tests, boxing-specific protocols, and boxing-specific incremental tests, which varied in type, structure, and applied context (de Oliveira et al., 2024; Herrera-Valenzuela et al., 2021; Jin et al., 2025).

Additional limitations emerged regarding the measurement tools used, including force platforms, instrumented targets, inertial sensors, accelerometers, heart rate monitors, metabolic analysers, and portable lactate analysers (Brown et al., 2022; Finlay et al., 2022; Liu et al., 2022; Venckunas et al., 2024). Although these tools have expanded the possibilities for performance monitoring, their methodological heterogeneity restricts direct comparison across studies.

The outcomes analysed mainly included indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics (Brown et al., 2022; Finlay et al., 2024; Wu et al., 2024). However, most studies focused on indicators of punching performance and physiological responses, whereas fewer investigations examined lower-limb neuromuscular characteristics. In particular, no study reported direct measurements of lower-limb muscle-tendon stiffness.

Overall, these findings suggest the need for methodologically integrated approaches capable of jointly analysing the principal components of boxing performance.

Qualitative synthesis

Punching performance

The included literature assigned a central role to indicators of punching performance, which were considered the principal reference for the evaluation of sport-specific performance in boxing. From a qualitative perspective, punching performance was examined through a heterogeneous set of indicators, mainly including punch impact force, punch velocity, and punch power (Cui et al., 2024a, 2024b; Jin et al., 2025; Liu et al., 2024).

Studies assessed punching performance in different experimental contexts. A substantial proportion of the literature employed maximal single-punch tests, generally performed using force platforms, instrumented targets, dummies, sensor-equipped punching bags, or systems based on accelerometers and inertial sensors (Kamandulis et al., 2018; Kim et al., 2018; Liu et al., 2022; Sánchez-Ramírez et al., 2025; Söyler et al., 2025). In other studies, attention shifted towards repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, and heavy-bag training, as well as protocols structured in rounds or with an intermittent work organisation, within which punching performance was also examined in relation to its changes over time (El-Ashker et al., 2018; Usher & Babraj, 2024; Xu et al., 2025). A further line of evidence concerned boxing-specific incremental tests, in which punching performance was analysed under progressively increasing intensity until exhaustion (de Oliveira et al., 2024; Venckunas et al., 2022).

Overall, the qualitative synthesis suggests that indicators of punching performance has been investigated both as a maximal expression, particularly in maximal single-punch tests, and as an expression of mechanical output during repeated or prolonged punching efforts typical of boxing-specific protocols. However, marked heterogeneity emerges in the variables considered, protocols adopted, and measurement systems used, which limits direct comparability between studies. Although a general consensus appears regarding the importance of indicators of punching performance as a central reference for sport-specific boxing performance, the methodological framework remains fragmented.

Indicators of punching performance therefore represent the most frequently analysed outcomes in the included literature, providing a robust characterisation of punching performance. However, these indicators have mainly been studied as independent variables, with limited integration with other components of performance. In particular, no systematic approaches have emerged that jointly examine indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics, highlighting the need for integrated models capable of providing a more comprehensive description of sport-specific performance in boxing.

Physiological responses

The physiological responses reported in the included literature mainly concerned heart rate, oxygen uptake, blood lactate concentration, and rating of perceived exertion (Chwała et al., 2023; de Lira et al., 2013; Finlay et al., 2018, 2024). These variables were investigated primarily during repeated or continuous boxing-specific punching protocols, including simulated bouts, sparring, pad work, and heavy-bag training, as well as protocols structured in rounds or with an intermittent work organisation (de Lira et al., 2013; El-Ashker et al., 2018; Ghosh, 2010), and during boxing-specific incremental tests (de Oliveira et al., 2024; Venckunas et al., 2022), aimed at quantifying physiological load during repeated efforts over time.

Regarding the instrumentation used, most studies employed heart-rate monitors for heart-rate assessment, portable or laboratory metabolic analysers for oxygen uptake measurement, and portable analysers for blood lactate determination (Brown et al., 2022; Hukkanen and Häkkinen, 2017; Venckunas et al., 2024). Additional measures were obtained through scales assessing perceived exertion (Thomson and Lamb, 2017a, 2017b; Xu et al., 2025).

Overall, the qualitative synthesis suggests that physiological responses have mainly been investigated as indicators of internal load associated with boxing-specific protocols. However, comparability between studies is limited by the marked heterogeneity of the variables considered, protocols adopted, and instruments employed, resulting in a methodologically fragmented framework.

Furthermore, although the available evidence describes the physiological responses associated with different boxing-specific protocols, these variables have predominantly been analysed independently rather than in direct relation to indicators of punching performance. In this context, no systematic and integrated analyses of the relationships between physiological responses and indicators of punching performance have emerged, highlighting the need for studies capable of simultaneously examining internal load and punching performance during boxing-specific protocols.

Lower-limb neuromuscular characteristics

Lower-limb neuromuscular characteristics were investigated in a still limited number of studies included in the present review, predominantly through explosive strength parameters derived from jump tests, such as the countermovement jump (CMJ) (Cui et al., 2024a; Finlay et al., 2024; Singh et al., 2025), or through maximal strength tests in the squat (1RM) (Kim et al., 2018; Niu et al., 2024; Wu et al., 2024). Among the principal parameters reported were jump height and, in some cases, variables such as force, power, rate of force development (RFD), and ground reaction force (GRF) (Brown et al., 2022; Chottidao et al., 2022; Dunn et al., 2022; Loturco et al., 2016). These parameters were generally considered expressions of lower-limb explosive capability and, in some studies, were analysed in relation to indicators of punching performance (Dunn et al., 2022; Loturco et al., 2021; Pinto et al., 2025).

With regard to instrumentation, most studies employed force platforms, contact mats, and optoelectronic systems (e.g. Optojump), mainly aimed at assessing lower-limb explosive strength parameters during jump testing (Finlay et al., 2024; Liu et al., 2024; Sánchez-Ramírez et al., 2025).

Table 2. Summary of findings and main limitations of the included studies.

Domain	Variables/ Outcomes	Methods/ Assessment	Main findings	Main limitations
Punching performance	Punch impact force; punch velocity; punch power; impulse; RFD; acceleration; effective mass; number/frequency of punches; cumulative output	Force platforms; instrumented targets; dummies; sensor-equipped punching bags; accelerometers; inertial sensors; video analysis systems; maximal single-punch tests; boxing-specific protocols; incremental tests	Punching performance represents the most extensively investigated domain and has been analysed both as a maximal expression of a single punch and as mechanical output during repeated or continuous punching efforts. This dual perspective allows the description of both maximal capability and performance over time.	The marked heterogeneity in variables considered, protocols adopted, and measurement systems used limits comparability between studies. Outcomes have mainly been analysed as independent variables rather than within integrated models, with limited integration with physiological responses and lower-limb neuromuscular characteristics.
Physiological responses	Heart rate; VO_2; blood lactate; rating of perceived exertion; pulmonary ventilation; respiratory rate; respiratory exchange ratio; muscle oxygenation; skin temperature	Heart-rate monitors; portable or laboratory metabolic analysers; portable lactate analysers; perceived exertion scales; boxing-specific protocols; incremental tests; training interventions	Physiological responses have primarily been investigated as indicators of internal load associated with boxing-specific protocols. Heart rate, VO_2, and blood lactate represent the most frequently investigated variables.	The marked heterogeneity in variables considered, protocols adopted, and instruments used limits comparability between studies. Physiological variables have mainly been analysed independently rather than in direct relation to punching performance, limiting understanding of the interactions between physiological load and sport-specific performance in boxing.
Lower-limb neuromuscular characteristics	Jump height; force; power; RFD; GRF; maximal squat strength	Force platforms; contact mats; optoelectronic systems (e.g. Optojump); CMJ; maximal squat strength tests (1RM)	Lower-limb neuromuscular characteristics have been less frequently investigated and have mainly been assessed through explosive strength parameters derived from jump tests. Some evidence indicates potential associations between selected variables (e.g. jump height, force, power) and indicators of punching performance.	The limited number of studies, the marked heterogeneity of tests used, and the frequent absence of integrated statistical analyses reduce the robustness of conclusions. Integrated analyses between explosive strength parameters and indicators of punching performance remain limited. Furthermore, no direct measurements of lower-limb muscle-tendon stiffness have been reported, nor have integrated approaches jointly examined its relationships with explosive strength and indicators of punching performance.

Note. CMJ = Countermovement Jump; GRF = Ground Reaction Force; 1RM = One-Repetition Maximum; RFD = Rate Of Force Development; VO_2 = Oxygen Uptake.

Overall, the qualitative synthesis suggests that some lower-limb neuromuscular characteristics, particularly specific explosive strength parameters, may be associated with indicators of punching performance. However, the limited number of studies, the marked heterogeneity of the tests employed, and the frequent absence of integrated statistical analyses reduce the robustness of current conclusions. In most of the included studies, lower-limb neuromuscular characteristics and indicators of punching performance were analysed independently or compared across experimental conditions, without direct assessment of their relationships. Moreover, the current literature does not report studies that have directly examined lower-limb muscle-tendon stiffness in boxing. This absence highlights an important knowledge gap and supports the need for integrated approaches that jointly examine muscle-tendon stiffness, lower-limb explosive strength, and indicators of punching performance. An additional limitation of the present review is the absence of a formal assessment of the methodological quality and risk of bias of the included studies. Therefore, the synthesized evidence should be interpreted while considering the potential methodological variability across studies and the differing robustness of the reported findings. Future systematic reviews should incorporate specific methodological quality assessment tools in order to provide a more accurate estimation of the strength of the available evidence.

To summarise the principal domains of analysis, variables considered, methodological approaches adopted, and main limitations emerging from the present qualitative synthesis, Table 2 is provided.

Towards an integrated model of boxing performance

The evidence emerging from the present review suggests that boxing performance should not be interpreted through the isolated analysis of single variables but rather considered as the result of the interaction between mechanical, physiological, and neuromuscular components. Although indicators of punching performance represents the most extensively investigated domain, the available literature shows limited integration between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics, resulting in a methodological and interpretative framework that remains fragmented.

In boxing, the ability to produce and maintain high levels of punching performance during intermittent high-intensity efforts represents one of the key aspects of sport-specific performance (Finlay et al., 2018; Loturco et al., 2016; Thomson & Lamb, 2017a, 2017b). In this context, physiological responses may be interpreted as expressions of the internal load imposed by the activity and of the athlete's capacity to sustain high-intensity actions over time (Franchini, 2020; Ruddock et al., 2021; Venckunas et al., 2022). Similarly, lower-limb neuromuscular characteristics, particularly explosive strength, may contribute to the production and maintenance of punching performance by influencing the athlete's ability to generate high levels of mechanical output during punching (Dunn et al., 2022; Loturco et al., 2016; Pinto et al., 2025). This interpretation is consistent with contemporary athlete monitoring models, according to which performance emerges from the interaction between external load, internal load, and the athlete's functional capacities. From this perspective, indicators of punching performance may be considered an expression of both external load and sport-specific performance output, whereas physiological responses represent the internal load imposed by the activity.

In parallel, lower-limb neuromuscular characteristics constitute a functional component capable of influencing both the production and maintenance of performance during intermittent high-intensity efforts. Although the available evidence does not allow definitive causal relationships to be established, the findings included in the present review suggest a potential interpretative model. In particular, the increase in physiological load associated with intermittent high-intensity efforts may contribute to the onset of fatigue-related phenomena capable of reducing the expression of lower-limb explosive strength. Such a reduction may compromise the effective transfer of forces along the kinetic chain and lead to a decrease in punching performance, particularly during the final stages of prolonged protocols or the concluding rounds of a bout. Conversely, superior lower-limb neuromuscular characteristics may contribute to maintaining mechanical output during punching despite the increase in physiological load, thereby supporting performance sustainability over time.

Despite these findings, the included studies have predominantly investigated these domains independently, limiting the understanding of the potential interactions between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics. In particular, the current literature does not yet clarify to what extent physiological responses and lower-limb neuromuscular characteristics may contribute to sport-specific performance in boxing.

An additional relevant aspect concerns lower-limb muscle-tendon stiffness. Although this property has been associated, in other sporting contexts, with the ability to optimize force production during dynamic and explosive actions (Brazier et al., 2019; Wdowski et al., 2023), none of the included studies directly investigated lower-limb muscle-tendon stiffness in boxing. This absence represents a relevant knowledge gap and highlights the need for future studies capable of integrating the analysis of muscle-tendon stiffness with the main lower-limb explosive strength parameters and with indicators of punching performance.

From this perspective, the adoption of multidimensional approaches could contribute to the development of more comprehensive methodological models for the analysis of boxing performance, promoting a deeper understanding of the interactions between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics. An integrated approach could also support the development of assessment, monitoring, and training prescription strategies more specifically oriented toward the demands of boxing performance.

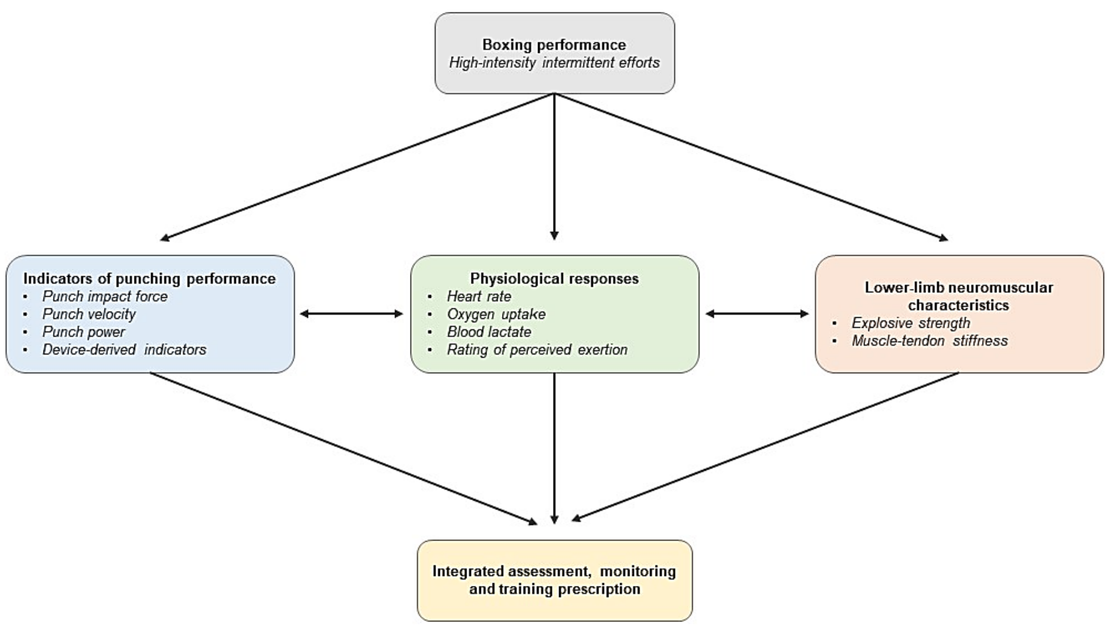

Figure 2. Integrated model of boxing performance.

The proposed integrated perspective is also consistent with recent developments in applied biomechanics, motor control, and performance analytics, disciplines that interpret sport performance as a complex system emerging from the interaction between multiple functional components (Raiola et al., 2025). In this context, the integration of mechanical, physiological, perceptual, and neuromuscular variables may support the development of predictive performance models and more comprehensive monitoring procedures, contributing to a multidisciplinary understanding of boxing performance.

The proposed integrated model of boxing performance is summarised in Figure 2.

Scientific and practical implications

The evidence emerging from the present review suggests the need to move beyond approaches based on the isolated analysis of single variables of boxing performance, promoting the development of integrated methodological models. In particular, the integration between indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics could contribute to a more comprehensive understanding of the main components of boxing performance and their potential interactions. From this perspective, boxing performance could be interpreted as the result of the interaction between the ability to produce high levels of mechanical output during punching, the ability to sustain the physiological load imposed by the activity, and the lower-limb neuromuscular characteristics involved in the production and maintenance of sport-specific performance.

From a scientific perspective, the findings of the present review highlight the need to develop integrated research approaches capable of simultaneously analysing the mechanical, physiological, and neuromuscular components of boxing performance. Such an approach could contribute to improving the understanding of the mechanisms associated with the production and maintenance of performance, while promoting the development of more comprehensive and in-depth methodological models for performance analysis. Furthermore, the limited integration observed between the different domains suggests the need for greater standardization of experimental protocols, assessment procedures, and measurement tools in order to improve the comparability of the available evidence.

From a practical perspective, an integrated approach could provide useful insights for optimizing boxing-specific training. In particular, the combined analysis of indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics could allow a more comprehensive and in-depth evaluation of the specific demands of boxing performance and of the capacities involved in sustaining and modulating punch intensity during repeated efforts over time. In this context, the use of portable devices and wearable sensors could support the development of more accessible assessment and monitoring procedures, facilitating the transfer of scientific evidence into applied practice.

Finally, the inclusion of boxers with different competitive levels and sex emerges as a particularly important aspect from both scientific and practical perspectives, contributing to addressing a relevant gap in the existing literature, which is often limited to homogeneous samples. The possibility of identifying differences in the mechanical, physiological, and neuromuscular components of performance could contribute to the development of more individualized training and monitoring strategies, oriented toward the specific characteristics of the athlete and the demands of boxing performance.

Future research directions

The evidence emerging from the present review suggests the need to develop future research lines oriented toward integrated and methodologically standardized approaches for the analysis of boxing performance. In particular, it appears necessary to overcome the tendency to investigate indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics separately, promoting studies capable of simultaneously analysing these domains within boxing-specific protocols. An integrated approach could contribute to a deeper understanding of the interactions between mechanical output during punching, physiological load, and lower-limb neuromuscular characteristics involved in the production and maintenance of performance during intermittent high-intensity efforts.

In particular, future research should develop integrated performance analysis models capable of simultaneously examining the contribution of mechanical, physiological, and neuromuscular variables through longitudinal and multidimensional approaches. Such models could contribute to a better understanding of the causal relationships between the different domains of performance and support the development of monitoring procedures more specifically oriented toward the demands of competitive boxing.

Another relevant aspect concerns the need for greater methodological standardization. The marked heterogeneity observed in experimental protocols, measurement tools, and analysed outcomes limits the comparability of the available evidence. Future research should therefore promote greater standardization of experimental protocols, measurement tools, and outcomes, in order to improve the comparability of evidence and support the development of integrated models for the assessment and monitoring of boxing performance. An important methodological consideration concerns the ecological validity of the protocols used in the available literature. Many studies have assessed different components of boxing performance through isolated tests or highly controlled conditions which, although ensuring high experimental precision, may not fully reflect the physiological, neuromuscular, and technical-tactical demands of actual boxing competition (D'Isanto et al., 2021; Giardullo et al., 2026; Ceruso et al., 2026). Future research should therefore promote the use of protocols that are more representative of competitive conditions, simultaneously integrating mechanical, physiological, and neuromuscular measures within applied and sport-specific contexts.

Particular attention should also be directed toward lower-limb muscle-tendon stiffness. Although evidence from other sporting contexts suggests a potential role of stiffness in force production during dynamic and explosive actions, none of the studies included in the present review reported direct measurements of lower-limb muscle-tendon stiffness in boxing. Future research should therefore further investigate the potential contribution of muscle-tendon stiffness to sport-specific performance in boxing and examine its relationships with the main lower-limb explosive strength parameters and with indicators of punching performance.

Future developments in research should also consider more systematically the differences associated with sex and competitive level. The available literature is still predominantly based on male samples, limiting the generalizability of the evidence. The inclusion of female boxers and mixed samples, as well as athletes from different competitive levels, could contribute to a more comprehensive understanding of the variables associated with boxing performance and their potential interactions.

Finally, future research could further explore the use of portable devices and wearable sensors for performance monitoring in more ecological and applied contexts. The integration of these technologies with multidimensional approaches could support the development of more accessible assessment and monitoring procedures directly transferable to sport practice, contributing to the advancement of scientific knowledge and practical applications in boxing and, potentially, in other combat sports.

CONCLUSIONS

The present systematic review highlighted that indicators of punching performance represent the most extensively investigated domain within the boxing literature, whereas physiological responses and lower-limb neuromuscular characteristics are still analysed in a relatively limited and frequently independent manner. Overall, the available evidence shows marked methodological heterogeneity in experimental protocols, measurement tools, and analysed outcomes, limiting comparability across studies and the possibility of developing an integrated understanding of boxing performance.

Current evidence suggests that boxing performance should be interpreted as the result of the interaction between the ability to produce high levels of mechanical output during punching, the ability to sustain the physiological load imposed by the activity, and the lower-limb neuromuscular characteristics involved in the production and maintenance of performance during intermittent high-intensity efforts. However, the limited integration observed between these domains still represents a relevant gap within the scientific literature.

Particular attention emerges regarding lower-limb neuromuscular characteristics. Although explosive strength has been associated in some studies with indicators of punching performance, none of the included studies reported direct measurements of lower-limb muscle-tendon stiffness in boxing. This absence highlights a relevant and still underexplored area of research and suggests the need to further investigate the potential contribution of muscle-tendon stiffness to sport-specific performance in boxing.

In this perspective, integrated and multidimensional approaches capable of simultaneously analysing indicators of punching performance, physiological responses, and lower-limb neuromuscular characteristics appear necessary. Such approaches could contribute to a more comprehensive understanding of the main components of boxing performance, support the development of integrated methodological models for performance assessment and monitoring, and provide useful insights for optimizing boxing-specific training.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: Giuseppe Penna. Methodology: Giuseppe Penna, Igor Jelaska. Formal analysis: Gaetano Altavilla. Investigation: Giuseppe Penna. Data curation: Giuseppe Penna, Igor Jelaska. Writing – original draft: Giuseppe Penna. Writing – review & editing: Igor Jelaska. Supervision: Gaetano Altavilla.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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