

Ecological dynamics analysis of muscle synergies and self-organization in rhythmic gymnastics

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ABSTRACT

Muscle synergies can be conceptualized, within ecological dynamics, as a self-organizing process. Studying muscle synergies in rhythmic gymnastics (RG) jumps may provide insight into how intermuscular coordination is organized in response to interacting constraints. Ankle weights are frequently used in RG training with the aim of improving jumping performance, although they may influence lower-limb coordination. Evidence on muscle synergies during RG jumps remains limited; therefore, this exploratory study aimed to examine how intermuscular coordination is organized during split leaps performed with and without 0.5 kg ankle weights, while also assessing selected biomechanical outcomes. The sample included six competitive RG gymnasts (16.5 ± 2.7 years). Data were collected using an integrated multifactorial optoelectronic system. In both conditions, two muscle synergy modules were extracted, showing similar muscle contribution patterns, whereas temporal activation profiles showed inter-individual variability. Pearson correlation coefficients indicated strong correlations between conditions for both muscle contributions ($|r| > .90$) and temporal activations ($.70 < |r| < .97$). S2 vertical displacement and flight time showed no clear systematic differences between conditions. These preliminary findings suggest relative preservation of the recorded lower-limb coordination structure under the additional load, which may be compatible with functional robustness in response to the task constraint.

Keywords: performance analysis, split leap, ankle weights, motor control.

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INTRODUCTION

Rhythmic gymnastics (RG) is defined as a technical-compositional sport (Liviotti & Hökelmann, 2012) and as a sport characterized by high demands on leap performance (Di Cagno et al., 2008). Accordingly, jumps represent one of the key technical components of RG routines and have received increasing attention in research. Previous research has examined several aspects of RG jumps, including take-off mechanics and technical execution (Coppola et al., 2020; Coppola et al., 2024; Loaiza-Navarro & Gamardo-Hernandez, 2018), landing strategies (Błażkiewicz et al., 2019), jumps performed with apparatus (Akkari-Ghazouani et al., 2020; Akkari-Ghazouani et al., 2023; Coppola et al., 2023), and variability between jumps performed with and without apparatus (Coppola et al., 2025). Jumps can be performed free body or by coordinating the handling of the ball, hoop, clubs, ribbon or rope (Yeh et al., 2019). Regarding run-up techniques, jumps can be performed using a chassé step, running (especially in the early stages of learning the movement), or a pre-jump (Costa et al., 2025).

One of the jumps most frequently performed by rhythmic gymnasts is the split leap (Örs & Turşak, 2020). It involves a sagittal split in flight, with the dominant leg moving forward and the non-dominant leg moving backward, to reach an amplitude of 180°. During the flight phase, the shape of the jump must be fixed and well defined with good elevation (Di Cagno et al., 2008). As described in the Fédération Internationale de Gymnastique (FIG, 2024) RG 2025–2028 Code of Points, this jump has a value of 0.30 points.

Jumps are considered highly dynamic motor tasks (Chiriac et al., 2021) that require strength and flexibility (Agopyan, 2021), adequate elevation and amplitude, balance during flight, and considerable inter- and intramuscular coordination (Marcolin et al., 2018). The ability to coordinate several muscles simultaneously in order to perform a motor task effectively can be investigated through muscle synergies, which consist of the coordinated activation of muscle groups over time and are thought to reduce the computational load associated with movement control (Esmaili & Maleki, 2019; Ranavolo, 2021). Within the broader motor control literature, muscle synergies have also been proposed as a modular mechanism that may simplify the organization of complex motor actions and reduce the computational demands associated with movement control (d'Avella, 2016; Ting & McKay, 2007). This perspective is particularly relevant in complex sport skills, where multiple muscles must be coordinated under changing task demands while preserving the functional organization of movement.

Within the theoretical framework of ecological dynamics, muscle synergies can be interpreted as a form of self-organization, namely, the functional organization of the body's degrees of freedom in relation to a goal (Button et al., 2020; Davids et al., 2008). Self-organization refers to spontaneous processes of adjustment and adaptation among system components in relation to changes in other parts of the system (Renshaw et al., 2019) and to their interaction with constraints (Rosengren et al., 2003). Among the range of possible movement solutions, a functional solution is one that enables the athlete to adapt effectively to interacting constraints. This adaptability is supported by the synergic organization of degrees of freedom that remain coupled and covary (Gray, 2021). Therefore, the abundance of degrees of freedom should be seen as a possibility to flexibly adapt and respond effectively to environmental variations (Newell & James, 2008; Latash et al., 2008). Furthermore, through the interaction with constraints, adaptive, creative and goal-oriented behaviours may emerge in the individual (Davids et al., 2013).

In this context, the choice to use ankle weights in this exploratory study, as a modification of task constraints (Newell, 1986), stems from their frequent use in RG training, where they are commonly adopted with the aim of enhancing jumping performance. However, although ankle weights introduce an additional external load,

they may also influence the organization of intermuscular coordination. Therefore, investigating muscle synergies during jumps in RG may provide preliminary insights into how intermuscular coordination is organized in response to modifications in task constraints. Integrating selected biomechanical outcomes may also help determine whether similarities in neuromuscular organization are accompanied by comparable characteristics of jump execution.

Some studies have examined the effects of ankle weights on motor performance during walking (Kunugi et al., 2024; Paquet et al., 2015) and taekwondo (Tarigan et al., 2022). However, to date, there appears to be no published research that has analysed muscle synergies during RG jumps or examined how they are influenced by the use of ankle weights. Therefore, the aim of this exploratory study was to investigate, through muscle synergy analysis and within an ecological dynamics framework, how intermuscular coordination is organized during split leaps performed with and without 0.5 kg ankle weights, while also examining selected biomechanical outcomes of jump execution.

MATERIALS AND METHODS

Sample

The study sample included six female competitive gymnasts (age: 16.5 ± 2.7 years; height: 164.2 ± 6.6 cm; body mass: 53.7 ± 4.8 kg; BMI: 19.97 ± 2.23 kg/m²).

Two athletes belonged to the Junior 2 category, while the other four were in the Senior category of the Italian Gymnastics Federation (FGI).

The athletes had competed during the year, had mastered the split leap, and used ankle weights during training. For all gymnasts, the right limb was dominant.

The gymnasts trained three times a week for two hours per session and reported no injuries at the time of data collection.

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

This study was conducted in accordance with the Declaration of Helsinki (World Medical Association [WMA], 2013) and was approved by the Ethical Committee of the Department of Human Sciences, Philosophy & Education at the University of Salerno (protocol number: 0044170).

Instruments

The BTS Bioengineering integrated multifactorial optoelectronic system was used in this study (BTS S.p.A., Italy). Specifically, the system consisted of seven BTS-6000 force platforms, six BTS FREEEMG surface electromyography sensors (sEMG), six BTS Smart-D video cameras, and two BTS-Vixta video support cameras. Marker trajectories were acquired at 70 Hz, sEMG signals at 1000 Hz, and force-platform data at 1120 Hz.

The force platforms were used to identify foot contact events with the ground. In addition, a passive reflective marker was applied to the athletes' bodies at the level of the second sacral vertebra (S2) to identify the event of maximum jump height.

Procedures

Data collection was carried out at the Laboratory for Innovative Teaching Methodologies and Analysis of Sports Performance at the University of Salerno (Italy). Before data acquisition, a pilot test was conducted in the same laboratory and with the same technologies on participants with characteristics similar to those of the study sample, to verify the feasibility and correct implementation of the protocol. A meeting was organized with the participating athletes and, in the case of underage athletes, with their parents/tutors, to provide all necessary information regarding the study procedures. For the study, each gymnast performed a standardized task-specific neuromuscular activation protocol.

Subsequently, a marker was placed at S2 on each athlete's body. The skin areas where the sEMG sensors were applied were then shaved and cleaned with alcohol. Six sEMG sensors were attached, three on the right lower limb and three on the left, following SENIAM recommendations (Hermens et al., 2000). Sensors were applied to the rectus femoris, biceps femoris, and gastrocnemius lateralis muscles.

Next, five trials of the split leap without ankle weights (Figure 1) and five trials of the same jump with ankle weights (Figure 2) were performed. Participants wore 0.5 kg ankle weights on each ankle, reflecting the load most commonly used in RG training. A two-minute recovery period was provided between the trials with and without weights. All gymnasts performed split leaps with the right leg leading and the left leg trailing, using a chassé step run-up technique.



Figure 1. Split leap performed without ankle weights.

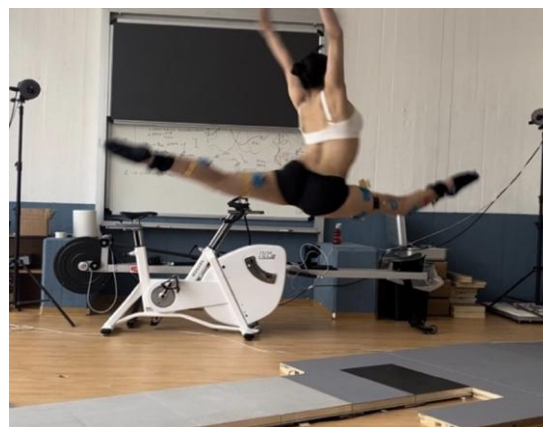


Figure 2. Split leap performed with ankle weights.

Data processing and analysis

SMARTanalyzer (BTS S.p.A., Italy) and MATLAB R2025a (The MathWorks, Inc, Natick, MA, USA) were used for data processing and analysis.

Event identification

Using the SMARTanalyzer software, a calculation protocol was created to identify four events: left foot contact with the force platform before the jump, take-off, maximum jump height, and landing. For muscle synergy analysis, left foot contact was identified from the vertical component of the Ground Reaction Force (GRF) and was defined as the first instant at which the force exceeded the 10 N threshold. Maximum jump height was identified from the vertical trajectory of the S2 marker and was defined as the instant at which the maximum value was recorded after take-off. For the biomechanical analysis, take-off was identified as the subsequent instant at which vertical GRF fell below 10 N, while landing was identified as the first subsequent instant at which vertical GRF exceeded 10 N.

Extraction of muscle synergies using Non-Negative Matrix Factorization (NNMF)

Initially, a high-pass filter at 20 Hz and a low-pass filter at 450 Hz were applied using SMARTanalyzer software. Subsequently, the sEMG signals were rectified, and the linear envelope was obtained by applying a 10 Hz low-pass filter. The sEMG signals were amplitude-normalized to the average of the maximum values recorded across trials. A selection of the sEMG signals was then performed, eliminating *outliers*, i.e. the curves that deviated most from the average signal pattern. This procedure left three trials for analysis. Subsequently, MATLAB R2025a was used to extract muscle synergies and compare the two conditions, namely split leaps with and without ankle weights. The extraction of the synergy modules for both conditions was carried out using *Non-Negative Matrix Factorization* (NNMF) (Lee & Seung, 2000), considering the time window from left foot contact to maximum jump height.

Variance accounted for (VAF) was used to quantify the goodness of fit between the measured and reconstructed data for each number of modules. The optimal number of modules was selected as the minimum number of modules for which the VAF exceeded 90% and the contribution to VAF obtained by adding one more module was less than 5% (Frère & Hug, 2012).

Cluster analysis

After muscle synergy extraction, cluster analysis was performed using MATLAB R2025a software. The obtained synergy modules were assigned to clusters based on the similarity of muscle composition using *k*-means analysis (Steele et al., 2015). Subsequently, to estimate the optimal number of clusters, silhouette scores were calculated for different *k* values (Hagio et al., 2021). The *k* value that produced the highest mean silhouette score was defined as the optimal number of clusters (Aoyama et al., 2022).

Cosine similarity

Cosine similarity (CS) was used to examine intra-cluster similarity. The cosine similarity for muscle contributions is shown in Figure 4a-b, while the cosine similarity for temporal activations is shown in Figure 5a-b. A cosine similarity threshold of $CS > 0.80$ was adopted as the criterion for considering two modules similar, in accordance with Oliveira et al. (2014).

Biomechanical analysis

Two biomechanical outcomes were analysed: S2 vertical displacement and flight time. S2 vertical displacement was calculated as the difference between the vertical position of the S2 marker at take-off and its maximum vertical position during the jump. Flight time was calculated as the time interval between take-off and landing. For both outcomes, the mean of three trials was calculated for each gymnast and condition.

Statistical analysis

To compare the trials with and without weights, the Pearson correlation coefficients were calculated between the clusters of the two conditions for both muscle contributions and temporal activations.

For each biomechanical outcome, the mean of the three selected trials was first calculated for each gymnast and condition, and these individual mean values were subsequently used for the group-level statistical analysis. Normality of the paired differences between conditions was assessed using the Shapiro–Wilk test. As the normality assumption was not violated, S2 vertical displacement and flight time were compared between conditions using paired-samples *t*-tests. Mean paired differences, 95% confidence intervals (CIs), and paired effect sizes (Cohen's d_z) were also calculated. Statistical significance was set at $p < .05$. Statistical analyses were performed using MATLAB R2025a. A schematic overview of the complete analytical workflow used in the study is provided in Figure 3.

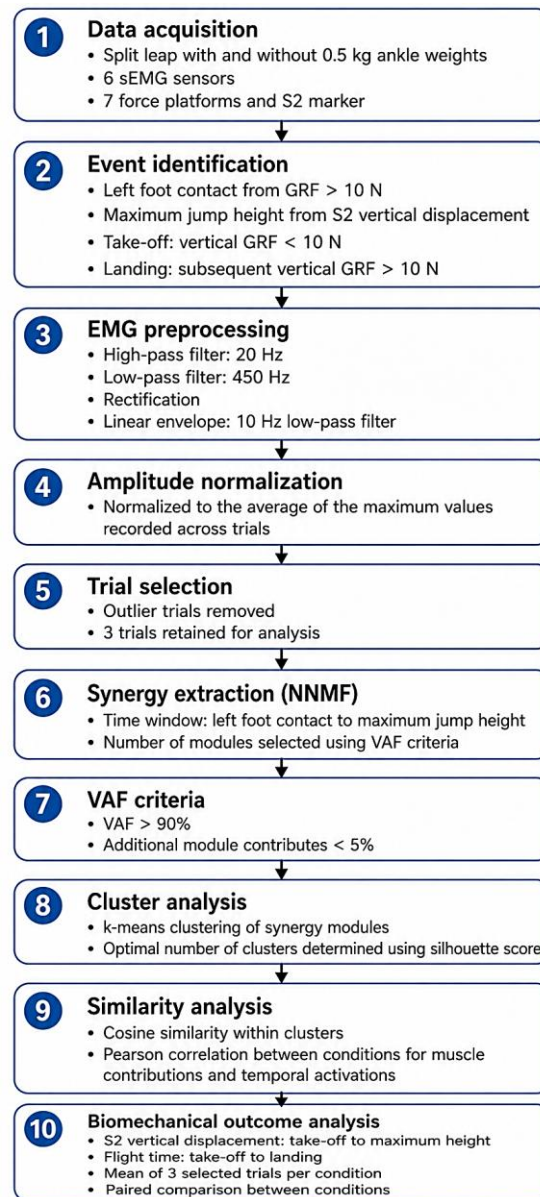


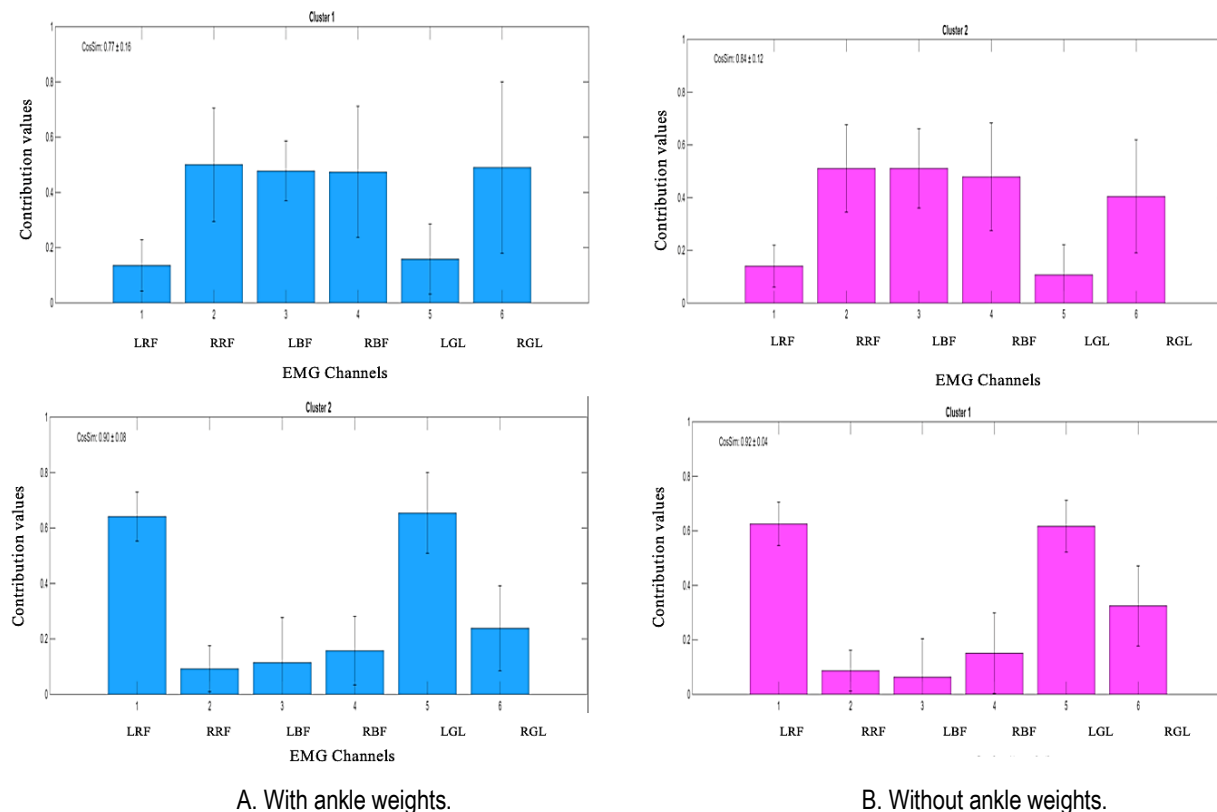
Figure 3. Schematic overview of the complete analytical workflow used in the study.

RESULTS

Muscle synergies

Muscle contributions

Two muscle synergy modules were identified across all gymnasts and in both conditions. The corresponding muscle contribution patterns are presented in Figure 4a-b. The panels were arranged to facilitate visual comparison between the conditions with and without ankle weights.



Note. Muscles: LRF = left rectus femoris; RRF = right rectus femoris; LBF = left biceps femoris; RBF = right biceps femoris; LGL = left gastrocnemius lateralis; RGL = right gastrocnemius lateralis. Panels: (a) blue bars represent jumps performed with 0.5 kg ankle weights: Cluster 1 (top) and Cluster 2 (bottom); (b) pink bars represent jumps performed without ankle weights: Cluster 2 (top) and Cluster 1 (bottom).

Figure 4. Muscle contributions of the two synergy modules during split leaps with and without ankle weights.

The first synergy pattern, illustrated in the top panels of Figure 4a-b, corresponded to Cluster 1 in the split leap with ankle weights and Cluster 2 in the split leap without ankle weights. This pattern was mainly characterized by the contribution of the right rectus femoris, bilateral biceps femoris, and right gastrocnemius lateralis, with mean CS values of 0.77 ± 0.16 in the condition with ankle weights and 0.84 ± 0.12 in the condition without ankle weights. The second pattern, shown in the bottom panels of Figure 4a-b, corresponded to Cluster 2 in the split leap with ankle weights and Cluster 1 in the split leap without ankle weights. This pattern was characterized by the contribution of the left rectus femoris and left gastrocnemius lateralis, with mean CS values of 0.90 ± 0.08 in the condition with ankle weights and 0.92 ± 0.04 in the condition without ankle weights.

Temporal activations

For temporal activations, cluster analysis identified six temporal activation clusters in the condition with ankle weights and five temporal activation clusters in the condition without ankle weights (Figure 5a-b).

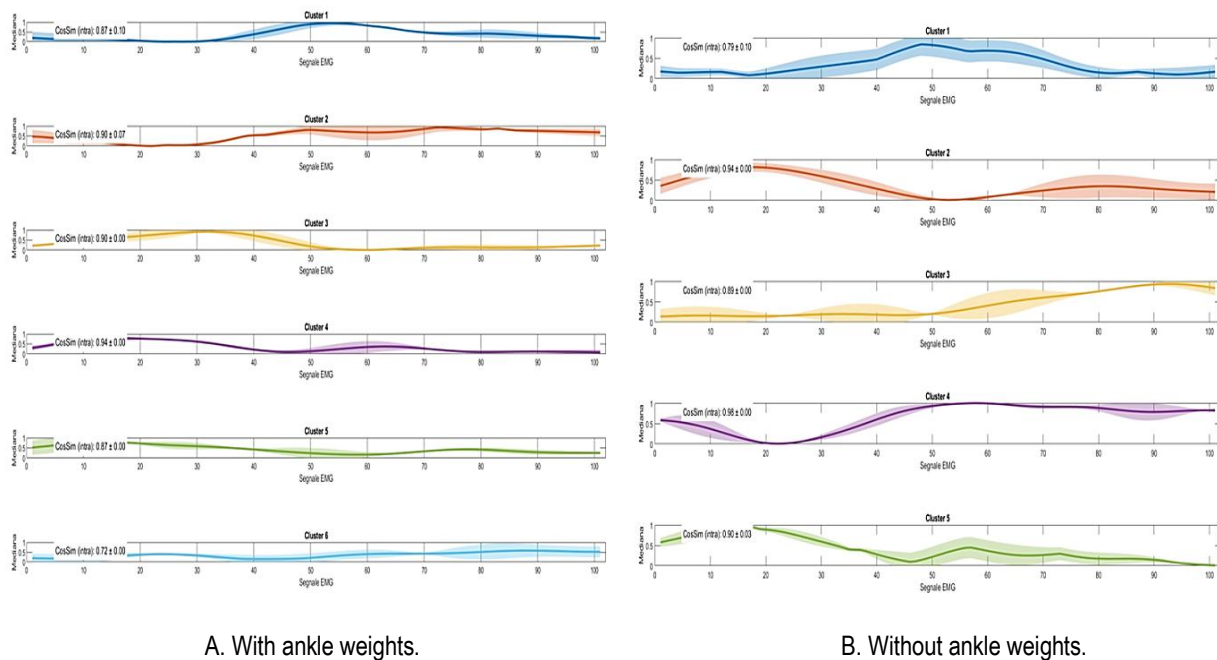


Figure 5. Temporal activations during the split leap with 0.5 kg ankle weights (a) and without ankle weights (b).

CS values for each cluster are reported in the corresponding panels and ranged from 0.72 to 0.94 in the condition with ankle weights, whereas in the condition without ankle weights they ranged from 0.79 to 0.98.

Pearson correlation coefficients between conditions were $|r| > .90$ for muscle contributions, while coefficients for temporal activations ranged from $.70 < |r| < .97$.

Biomechanical outcomes

S2 vertical displacement

Table 1. Individual S2 vertical displacement with and without ankle weights.

Gymnast	With ankle weights (cm)	Without ankle weights (cm)	Δ (with – without ankle weights) (cm)
Athlete 1	12.26 $\pm$ 1.39	12.80 $\pm$ 0.53	-0.54
Athlete 2	17.17 $\pm$ 1.99	18.94 $\pm$ 1.91	-1.77
Athlete 3	14.72 $\pm$ 1.43	12.82 $\pm$ 1.38	+1.90
Athlete 4	13.35 $\pm$ 1.45	16.43 $\pm$ 2.01	-3.08
Athlete 5	13.42 $\pm$ 2.13	16.54 $\pm$ 3.45	-3.12
Athlete 6	11.60 $\pm$ 3.17	9.54 $\pm$ 1.88	+2.06

Note. Values are presented as mean $\pm$ SD across the three selected trials for each gymnast. Δ was calculated as the condition with ankle weights minus the condition without ankle weights.

At the group level, mean S2 vertical displacement was 13.75 ± 1.99 cm with ankle weights and 14.51 ± 3.40 cm without ankle weights. The mean paired difference (Δ = with – without ankle weights) was -0.76 cm (95% CI $[-3.20, 1.68]$ cm). The paired differences did not significantly deviate from normality (Shapiro–Wilk $W = 0.865$, $p = .207$). The paired-samples t -test yielded $p = .461$, with $d_z = -0.33$.

Flight time

Table 2. Individual flight time with and without ankle weights.

Gymnast	With ankle weights (s)	Without ankle weights (s)	Δ (with – without ankle weights) (s)
Athlete 1	0.376 ± 0.007	0.397 ± 0.014	-0.021
Athlete 2	0.446 ± 0.002	0.418 ± 0.045	$+0.028$
Athlete 3	0.377 ± 0.006	0.367 ± 0.008	$+0.010$
Athlete 4	0.429 ± 0.013	0.439 ± 0.014	-0.010
Athlete 5	0.412 ± 0.011	0.420 ± 0.015	-0.008
Athlete 6	0.382 ± 0.011	0.371 ± 0.003	$+0.011$

Note. Values are presented as mean $\pm$ SD across the three selected trials for each gymnast. Δ was calculated as the condition with ankle weights minus the condition without ankle weights.

At the group level, mean flight time was 0.404 ± 0.030 s with ankle weights and 0.402 ± 0.029 s without ankle weights. The mean paired difference (Δ = with – without ankle weights) was 0.002 s (95% CI $[-0.017, 0.020]$ s). The paired differences did not significantly deviate from normality (Shapiro–Wilk $W = 0.950$, $p = .742$). The paired-samples t -test yielded $p = .821$, $d_z = 0.10$.

DISCUSSION

This exploratory study examined the effects of 0.5 kg ankle weights on muscle synergies during the split leap in RG. Evidence on muscle synergies in RG jumps remains limited, particularly regarding the influence of external loading such as ankle weights. Beyond describing similarities in muscle synergies between conditions, the findings were interpreted within an ecological dynamics framework, with particular attention to constraint-induced coordination, inter-individual variability, and functional organization under task constraints.

From the Pearson correlation analysis, very high correlation coefficients ($|r| > .90$) were observed for muscle contributions between jumps performed without ankle weights and those performed with 0.5 kg ankle weights across the entire sample (Yagin et al., 2024). For temporal activations, correlation coefficients ranged from $.70 < |r| < .97$, indicating strong associations between the two conditions (Yagin et al., 2024). These high correlations indicate strong associations between conditions but should not be interpreted as evidence of statistical equivalence.

Collectively, these results suggest that, for the muscles investigated, intermuscular coordination remained similar across conditions despite the addition of 0.5 kg ankle weights. Within this exploratory sample, the recorded lower-limb muscle set appeared to maintain a similar coordination structure across conditions, which may be compatible with functional stability in response to the task constraint and with the maintenance of the technical structure of the skill, as defined by the requirements of the RG 2025-2028 Code of Points. This relative preservation may reflect a degree of functional robustness in the recorded lower-limb coordination.

According to the constraints-led approach (Newell, 1986), manipulating task constraints, for example by using ankle weights, can be useful for providing a functional level of overload and for challenging performance-related adaptations (Brazil et al., 2020). In this study, the muscle contribution structure remained relatively stable despite the addition of an external load.

The results for muscle contributions show that one synergy pattern (Figure 4a-b) corresponding to Cluster 1 in the split leap performed with ankle weights and Cluster 2 in the split leap without ankle weights, was mainly characterized by higher contributions from the right rectus femoris, bilateral biceps femoris, and right gastrocnemius lateralis. The predominance of right-limb muscles in this pattern may reflect the role of the right leg in producing the forward swing for the jump execution.

A second pattern (Figure 4a-b), corresponding to Cluster 2 in the split leap with ankle weights and Cluster 1 in the split leap without ankle weights, was characterized by the left rectus femoris and the left gastrocnemius lateralis, which may be involved in controlling left-leg contact with the ground.

These results are consistent with the findings of Navacchia et al. (2019) and Alter (2004), who described the main muscles active during jumping as the hamstrings for hip extension, the quadriceps femoris for knee extension, and the gastrocnemius for ankle plantar flexion.

Across the conditions with and without ankle weights, the muscle contribution patterns were largely preserved, whereas the temporal activation profiles differed. Intra-cluster similarity varied across patterns. Most muscle contribution clusters showed mean CS values consistent with or close to the predefined 0.80 similarity threshold (Oliveira et al., 2014). Temporal activation clusters showed greater variability, with some mean CS values falling below the predefined threshold.

Differences observed in temporal activation profiles between gymnasts (Figure 5a-b) may be consistent with the principle of inter-individual variability in muscle coordination (Hug et al., 2010). Within an ecological dynamics framework, in which coordination is understood as emerging through self-organization in relation to interacting constraints (Button et al., 2020; Davids et al., 2008), the observed inter-individual differences may be interpreted as reflecting distinct coordination strategies in response to the task constraints.

From an ecological dynamics perspective, these findings may be interpreted as being compatible with adaptable and constraint-dependent coordination (Button et al., 2020; Davids et al., 2008). The addition of ankle weights modified the task constraints by increasing the external load, while the overall muscle contribution patterns remained largely preserved. This may suggest that coordination was sufficiently stable to accommodate the imposed constraint without requiring a marked reorganization of the recorded lower-limb muscle contributions. At the same time, the variability observed in temporal activation patterns between gymnasts highlights that similar task goals may be achieved through different individual coordination solutions. Such inter-individual variability may be viewed as a functional feature of movement organization rather than merely as noise, reflecting the availability of multiple ways to coordinate the system in relation to the same performance goal (Newell & James, 2008; Latash et al., 2008). Within this theoretical framework, this flexibility is also compatible with the concept of degeneracy, whereby structurally different system configurations may contribute to functionally similar outcomes (Seifert et al., 2016). However, adaptability and degeneracy were not directly measured in the present study and should therefore be considered theoretical interpretations of the observed coordination patterns.

Several studies have analysed muscle synergies in different motor tasks such as walking (Chvatal & Ting, 2013; Escalona et al., 2021; Hagedoorn et al., 2022), running (Coiro et al., 2025; Nishida et al., 2017; Saito et al., 2018), cycling (De Marchis et al., 2013; Esmaeili & Maleki, 2019), jumping (Rodrigues et al., 2017), balance postures (Moiseev & Mikhaylova, 2023), ball throwing (Moiseev & Ivanov, 2024) and ball catching (Moiseev et al., 2026). Across these different motor tasks, muscle synergy research suggests that coordination may retain relatively stable organizational features while also exhibiting task- and individual-specific adjustments. The broadly preserved muscle contribution patterns observed in the present study may be considered consistent with this general perspective. However, direct comparison remains limited because evidence specifically examining muscle synergies during RG jumps is scarce. Nevertheless, findings from other motor tasks may provide a broader context for interpreting how coordination is organized under changing constraints. In this context, rhythmic gymnastics may provide a useful task environment for examining how coordination is maintained or reorganized during technically constrained actions that require precise spatial and temporal organization. Given the exploratory nature and small sample of the present study, these findings should be considered preliminary evidence that may inform future comparative research across complex sport skills.

The biomechanical outcomes provide additional context for these findings. S2 vertical displacement (shown in Table 1) did not show a clear systematic difference between conditions at the group level. Although four of the six gymnasts showed lower values with ankle weights, the 95% CI for the paired difference included zero, indicating that the observed data were compatible with both a reduction and an increase in S2 vertical displacement. Flight time (shown in Table 2) was also very similar between conditions at the group level, with three gymnasts showing longer flight times with ankle weights and three showing shorter flight times. Overall, these findings suggest that the preserved lower-limb synergy structure occurred alongside relatively similar S2 vertical displacement and flight time within the present exploratory sample. However, the absence of statistically significant differences, together with the small effect sizes ($d_z = -0.33$ for S2 vertical displacement; $d_z = 0.10$ for flight time) (McGuigan, 2017), should not be interpreted as evidence of biomechanical equivalence between conditions.

From a practical perspective, the present findings suggest that 0.5 kg ankle weights may be used as an additional external load during split-leap practice while preserving both the lower-limb coordination structure and the selected biomechanical characteristics of the jump observed in the unloaded condition. Coaches may therefore consider 0.5 kg ankle weights as a task constraint that may be incorporated into split-leap practice, while taking into account the individual responses observed across gymnasts.

Limitations

The primary limitation of this exploratory study is the small sample size ($n = 6$), which limits the generalizability of the findings and the extent to which the extracted synergy patterns can be considered stable and reproducible across rhythmic gymnasts. The inter-individual variability observed in the present sample should also be considered when interpreting these findings.

Data collection was carried out in a human movement analysis laboratory, which differs from the typical RG training and competition environment. In addition, the high execution speed of the split leap required the application of adhesive tape to keep the sEMG sensors fixed on the athletes' bodies. A further limitation concerns the restricted EMG muscle set, which included only six lower-limb muscles. Therefore, the extracted synergies represent a partial model of the neuromuscular coordination involved in the split leap and do not capture the contribution of other muscles involved in hip stabilization, trunk control, or upper-body organization.

CONCLUSIONS

The findings of this exploratory study revealed strong to very strong correlations for both muscle contributions ($|r| > .90$) and temporal activations ($.70 < |r| < .97$) between jumps performed with and without 0.5 kg ankle weights. These preliminary findings suggest that, within the present sample, the recorded lower-limb muscle synergy structure was preserved when split leaps were performed with 0.5 kg ankle weights. Rather than indicating an absence of change in the recorded neuromuscular patterns, this relative preservation may be compatible with a degree of functional stability or robustness of coordination in response to the imposed task constraint. In addition, S2 vertical displacement and flight time did not show clear systematic differences between conditions at the group level, suggesting relatively similar values for these selected biomechanical characteristics of the jump. Taken together, the neuromuscular and biomechanical findings may reflect a degree of functional robustness in response to the modest external task constraint imposed by 0.5 kg ankle weights.

In conclusion, this exploratory study provides preliminary evidence on the organization of lower-limb muscle synergies during split leap execution under an external loading constraint. Future research should include larger and more diverse samples across different competitive levels to determine whether the observed coordination patterns are stable and reproducible across rhythmic gymnasts. Further studies should also extend the analysis to other types of jumps, include a broader set of lower-limb, proximal, trunk, and potentially upper-body muscles, and examine whether training with ankle weights transfers to split-leap execution in competition contexts.

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: Claudia Costa, Silvia Coppola, Rodolfo Vastola. Methodology: Claudia Costa, Silvia Coppola, Maria Teresa Benincasa, Enrico Serra. Formal analysis: Claudia Costa, Ester Celentano, Maria Teresa Benincasa, Francesco Coiro. Investigation: Claudia Costa, Silvia Coppola, Ester Celentano. Data curation: Claudia Costa, Francesco Coiro, Enrico Serra. Writing – original draft: Claudia Costa, Silvia Coppola. Writing – review & editing: Claudia Costa, Silvia Coppola, Ester Celentano, Enrico Serra, Maria Teresa Benincasa, Francesco Coiro, Rodolfo Vastola. Supervision: Rodolfo Vastola.

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.

ETHICAL CONSIDERATIONS

These trials were conducted in accordance with the ethical principles of the Declaration of Helsinki (WMA, 2013). The study was approved by the Ethical Committee of the Department of Human Sciences, Philosophy & Education at the University of Salerno (protocol number: 0044170).

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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