

Differences in self-organizing patterns between acceleration and maximum velocity phases in sprinting: A pilot study based on muscle synergy analysis

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Abstract:

In the framework of the ecological–dynamic approach, muscle synergies represent the inherent self-organizing mechanisms that emerge from the interaction between an individual and their environment, driving them toward achieving specific goals. These synergies simplify motor control by reducing complexity stemming from the presence of numerous degrees of freedom. This enables the system to adjust to changing environmental demands while maintaining stability in performance. As a result, studying muscle synergies has become a widely recognized approach for understanding neuromuscular control across various motor tasks in recent decades. Nevertheless, despite extensive research on muscle synergies during running at different speeds, no investigations have explicitly compared muscle synergies during the acceleration phase with the maximal velocity phase of a sprint. This pilot study aims to fill this gap in the literature by analyzing muscle synergies in both phases. To test the hypothesis positing that the neuromuscular system uses different self-organizing strategies in accordance with the specific goals of the two primary phases of a sprint, three male subjects performed three maximal 30-m sprints. During these sprints, electromyographic signals were recorded from eight muscles of the dominant lower limb. The data were analyzed using non-negative matrix factorization (NMF) to extract muscle synergy modules. The findings demonstrate that the neuromuscular system uses three synergy modules during the acceleration phase and two during the maximal velocity phase. This disparity suggests that the system tailors its self-organizing patterns to the different objectives of the two sprint phases. These findings may help coaches select exercises that ensure optimal training transfer. Future research should expand the sample size and examine the impact of environmental factors on self-organizing patterns during maximal sprints on a track compared to other field types.

Keywords: Muscle Synergies, Sprint Running, EMG, Non-Negative Matrix Factorization, Motor Control

Introduction

The performance model of many sports, including soccer and rugby, emphasizes high-speed running and repeated bursts of acceleration over brief distances (Dolci et al., 2020; Faude et al., 2012; Oliva-Lozano et al., 2020). In the literature, sprint running is commonly classified into distinct phases: acceleration (initial phase and transition) and maximal velocity, each with unique spatial, temporal, and kinematic characteristics (von Lieres Und Wilkau et al., 2020; Schache et al., 2019; Nagahara et al., 2018; Nagahara et al., 2014).

During the acceleration phase, the vector connecting the athlete's center of mass to the ground contact point is tilted forward (von Lieres Und Wilkau et al., 2020). This posture, characterized by the inclination of the trunk and leg, enables the ground reaction force (GRF) vector to be optimally oriented for generating the forward-propulsive force necessary for rapid acceleration of the center of mass (Schache et al., 2019; Haugen et al., 2019; Kugler & Jansher, 2010). The force production required for effective acceleration is further facilitated by extended contact times (Wild et al., 2011). As the sprint progresses, the athlete gradually transitions to a more upright posture, realigning the GRF vector to prioritize vertical force production while reducing horizontal propulsive force (Schache et al., 2019). This adjustment helps counteract the effects of gravity, reduce contact times, and increase flight times and step length (Rabita et al., 2015; Wild et al., 2011).

These differences reflect the unique goals of each phase: achieving high locomotion speeds rapidly by generating horizontal propulsive forces during the acceleration phase and sustaining constant speed using elastic energy during the maximal velocity phase (Haugen et al., 2019; Albano et al., 2019). Numerous studies have examined EMG activations of various muscles throughout the running cycle, identifying distinct muscle activation patterns in the two sprint phases (Pandy et al., 2021; Higashihara et al., 2018; Morin et al., 2015). However, muscles do not work in isolation; instead, they coordinate and work together to produce movement. As a result, investigating the underlying coordinative dynamics of sprint movements is crucial. Understanding the

coordinative differences between the acceleration and maximal velocity phases could assist coaches in selecting exercises that maximize training transfer.

The human body is a complex system characterized by high motor redundancy, which poses challenges to its control. Bernstein (1967) referred to this "abundance of degrees of freedom" as the fundamental problem of motor control. Degrees of freedom represent the number of ways in which the system can vary independently (Rosenbaum, 2009). Each joint in the body, based on its anatomical structure, possesses two to six degrees of freedom; when we consider the number of joints involved in any movement and sum their degrees of freedom, redundancy becomes evident (Rosenbaum, 2009). This redundancy extends beyond joint movement possibilities to include muscle activations, as the same joint movement can be generated by activating different muscles (Latash, 2012; Latash et al., 2008). This translates into the possibility of achieving the same motor task in an infinite number of ways (Latash, 2012). To manage this complexity, it is hypothesized that the central nervous system (CNS) uses various strategies, including muscle synergies, which represent groups of muscles that work together (Bernstein, 1967). Instead of viewing the abundance of degrees of freedom as a computational challenge for the CNS, it should be recognized as a feature that enables the system to adapt and respond to variations and perturbations (Coppola et al., 2025; Latash et al., 2008). Muscle synergies can be conceptualized as the "movement dictionary," where muscles represent the letters of the alphabet, and synergies are combinations of these letters to form words (Kelso, 1995).

Numerous studies have demonstrated that motor actions in vertebrates can be decomposed into fundamental coordinative structures known as motor modules or muscle synergies, which simplify the complexity of motor control (Bizzi & Cheung, 2013; Cappellini et al., 2006; Cheung et al., 2005; d'Avella et al., 2003; Hogan & Sternad, 2013; Latash, 2020). In the theoretical framework of the ecological–dynamic approach (Araújo, 2006), muscle synergies represent the system's self-organizing tendencies in relation to specific goals (Davids, 2008). During the execution of a motor task, they emerge from continuous body–environment interactions involving a constant exchange of information (Kelso, 1994; Newell, 1986). Among the wide range of possible movement solutions, the optimal solution can be defined as the one that enables the athlete to adapt most effectively to the constraints they encounter. This adaptability is facilitated by the synergistic action of degrees of freedom that remain coupled and covary (Gray, 2021). Synergies allow the system to respond to perturbations by modulating synergy components or neighboring synergy components (Kelso, 2022), ensuring the stability of system performance (Latash et al., 2008).

Complex biological systems thus address two main challenges of motor control: degeneration, or the ability to achieve the same outcome by coordinating different components, and multifunctionality, or the ability to achieve different outcomes using the same components (Kelso, 2022). In recent decades, studying muscle synergies has emerged as an effective approach to exploring neuromuscular control in various motor tasks, such as walking (Kim et al., 2016; Cappellini et al., 2006), throwing (Aoyama et al., 2024; Aoyama et al., 2022), and running (Saito et al., 2018; Nishida et al., 2017; Yokoyama et al., 2016; Hagio et al., 2015; Lacquaniti et al., 2012).

While muscle synergies during walking and running at various speeds have been extensively investigated (Yokoyama et al., 2016; Hagio et al., 2015), no studies have directly compared muscle synergies between the acceleration and maximal velocity phases of maximal sprint running. Addressing this gap is crucial for understanding how the neuromuscular system dynamically adapts to the distinct demands of each running phase. This pilot study aims to bridge this gap by analyzing muscle synergies during the acceleration and maximal velocity phases of sprint running. The aim is to investigate the presence of distinct self-organizing patterns in the two phases by analyzing muscle synergies.

Materials and methods

Participants

A convenience sample of three male subjects (mean age: 25.6 ± 2.08 years) was selected for the study. The subjects had an average height of 175 cm (± 5 cm) and weighed of 72 kg (± 4 kg). Each subject had approximately 6 years (6.6 ± 0.58 years) of sprint training experience. All subjects were right-limb dominant, free of any orthopedic or neurological abnormalities, and had not experienced lower-limb muscle injuries in the past 6 months.

Procedures and Measurements

All participants were informed of potential risks and provided written informed consent for participation in this study, which was performed in accordance with the Declaration of Helsinki. The study was approved by the Ethics Committee of the Department of Human, Philosophical, and Educational Sciences of the University of Salerno (protocol number: 0186309). The study was designed and coordinated by the research staff of the Laboratory for Innovative Teaching Methodologies and Analysis of Sports at the University of Salerno (UNISA).

The experimental session was performed at the indoor sports hall of the University Sports Center (CUS Salerno), which is equipped with Taraflex flooring. Environmental conditions were controlled, with an ambient temperature of $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and a relative humidity of $60\% \pm 2\%$. Participants were instructed to refrain from

high-intensity running training for 24 h before the session and to avoid taking medications, alcohol, caffeine, or any other substances that could affect their performance.

Before testing, participants completed a standardized warm-up. This consisted of a 5-min period of progressively intensifying running, followed by 5 min of dynamic stretching and sprint-specific drills. The warm-up culminated in five submaximal sprints covering a distance of 15 m each. Participants then performed three maximal sprints of 30 m, with a 2-min rest interval between each trial. The 30-m sprint distance was chosen because it approximates the distance at which team sport athletes typically attain maximal running speed (Rumpf et al., 2016). Sprints shorter than 30 m (15–20 m) primarily constitute acceleration phases. To minimize the impact of muscle fatigue on muscular synergy contributions, the number of sprint trials was set at three, with sufficient 2-min recovery periods (Hajiloo et al., 2020).

Surface electromyography (EMG) signals were acquired from the eight muscles exhibiting the highest activity during running in the dominant lower limb (Gazendam et al., 2007). These muscles were gluteus maximus (GM), biceps femoris (BF), semitendinosus (ST), lateral gastrocnemius (GL), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), and tibialis anterior (TA). Surface EMG wireless sensors (BTS FREEEMG 1000 H2O, BTS Bioengineering) were used with a sampling frequency of 1000 Hz. The electrodes were 24 mm diameter Kendall H124SG EMG electrodes, placed with a 20 mm inter-electrode distance at sites recommended by the SENIAM guidelines (Hermens et al., 2000). Before placement, the skin was prepared by shaving and cleaning with abrasive and conductive gel. To minimize noise from sensor movement and prevent detachment during sprint running, the sensors were secured with tape.

An inertial sensor (BTS G-Sensor, BTS Bioengineering) with a sampling frequency of 100 Hz was secured at the lumbar vertebrae level using an elastic band to define the running cycles.

Analysis

In the BTS SMARTanalyzer software, raw EMG signals from the eight muscles were band-pass filtered in a frequency range of 20–450 Hz. Subsequently, the signals were rectified, and their envelopes were extracted using a low-pass filter with a cutoff frequency of 10 Hz. The EMG amplitude for each muscle was normalized relative to its peak activation during each cycle (Aoyama et al., 2022).

Running cycles were identified based on the analysis of angular velocities along the vertical axis of the G-sensor. A negative value indicated a leftward rotation of the sensor, corresponding to right-foot contact. Thus, all negative peaks were identified as reference points for defining running cycles. The first negative peak was excluded, while the subsequent three peaks were used as contact events for defining acceleration phase cycles. Maximal velocity phase cycles were defined by excluding the first four peaks and considering the next four.

Each running cycle was temporally normalized, and the mean muscle activation across all cycles was calculated for both the acceleration and maximum velocity phases. This yielded the average activation value for each muscle during a typical running cycle (Aoyama et al., 2022). For each trial, the duration of the running motion (defined as the interval between the initial foot contact and the subsequent contact of the same foot) was normalized to 101 data points (0%–100% of the running cycle) using cubic spline interpolation (Aoyama et al., 2022).

Synergy modules were extracted in MATLAB (MathWorks) using non-negative matrix factorization (NMF) (Lee et al., 1999). NMF is considered the most reliable algorithm among various synergy extraction algorithms for analyzing synergies in dynamic actions such as walking and running (Tresch et al., 2006; Rabbi et al., 2020). NMF reduces the dimensionality of EMG data from multiple muscles to a limited set of significant variables that represent synergies. It extracts components with similar spatial, temporal, or spatiotemporal activation patterns, producing synergy activation coefficients (C), which reflect the time-resolved contribution of each synergy, and muscle synergy vectors (W), or muscle weights, which indicate each muscle's contribution to the synergy (Hug et al., 2010).

Specifically, NMF decomposed the non-negative matrix of EMG data (M) from 8 muscles $\times$ 101 temporal points into a combination of time-invariant components W_i and time-variant activation weights c_i (d'Avella et al., 2003):

$$M = c_1W_1 + c_2W_2 + \dots + c_nW_n$$

The algorithm was iterated until the squared error between the original and reconstructed EMG data was less than 10^{-6} or up to a maximum of 500 iterations. The optimal number of synergy modules was determined as the point where the variance accounted for (VAF) exceeded 90%, with any additional module contributing less than 5% to the VAF (Aoyama et al., 2022).

After the extraction of synergy modules, cross-correlation analysis (Hug et al., 2011) was performed to compare the temporal activation of synergy modules between the acceleration and maximal velocity phases. Additionally, the Pearson correlation coefficient was calculated to compare muscle contributions in the synergy modules across both phases (Hug et al., 2010). Two modules were considered similar if their correlation values exceeded 0.8, based on our observations.

Results

The VAF values obtained using up to 8 modules for both the acceleration and maximal velocity phases are shown in Figure 1.

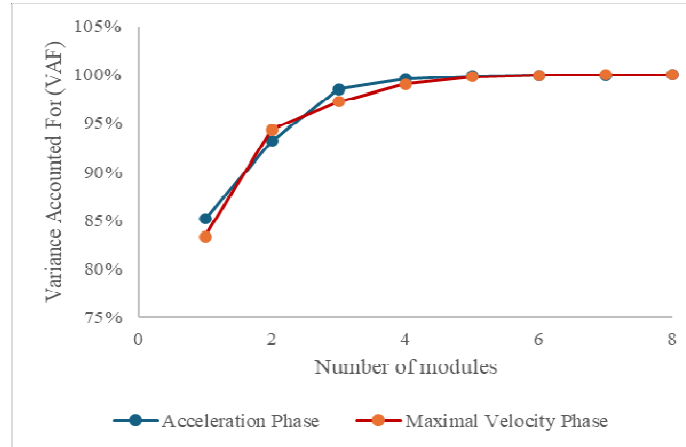


Figure 1. Variance accounted for (VAF) for the acceleration and maximal velocity phases

During the acceleration phase, extracting 3 modules resulted in a VAF of 98.51%, with the subsequent module only providing an additional 1.09%. The composition of each individual synergy module for this phase is shown in Figure 2.

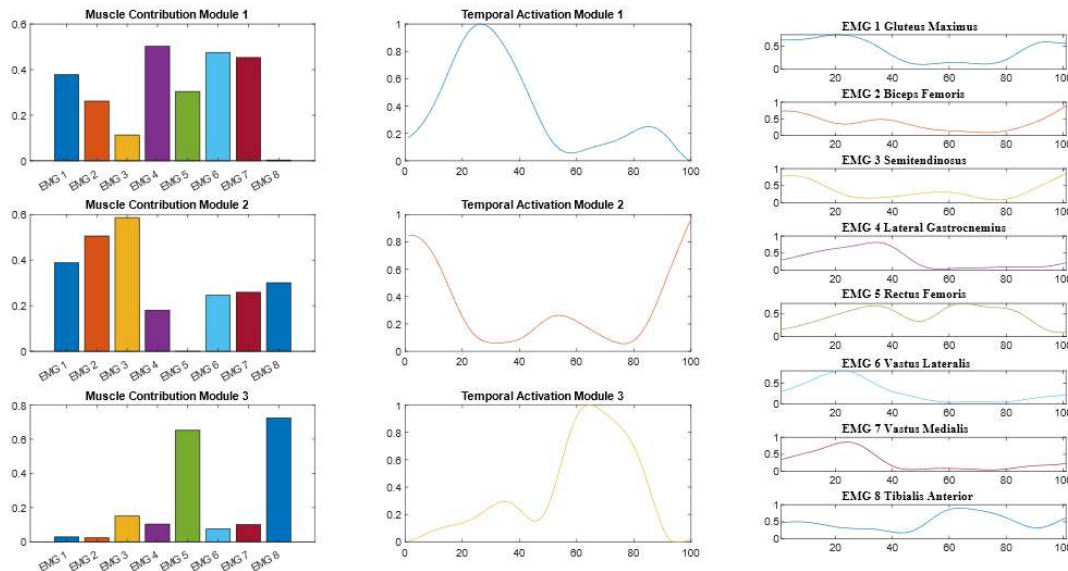


Figure 2. Synergy modules of the acceleration phase. On the left, histograms show the muscular contributions of individual muscles to the different synergy modules. In the center, Cartesian diagrams depict the temporal activation of the synergy modules. On the right, the EMG signals of individual muscles are displayed.

Synergy module 1 exhibited increased muscular contributions from the GL, VL, VM, and GM muscles. In contrast, synergy module 2 demonstrated greater muscular contributions from the ST, BF, and GM muscles. Finally, synergy module 3 displayed predominant muscle activation in the RF and TA muscles. The temporal activations of the three modules follow a sequential pattern. Module 2 exhibits an activation peak during the initial 20% of the running cycle, followed by activation of module 1 from 20% to 40%. Subsequently, module 3 becomes active from 50% to 80%, concluding with a second activation peak of module 2 between 90% and 100% of the running cycle.

During the maximal velocity phase, only two synergy modules were sufficient to achieve a VAF value of 94.37%. An additional module contributed only a marginal 2.87% more to the VAF. The composition of each individual module in this phase is shown in Figure 3.

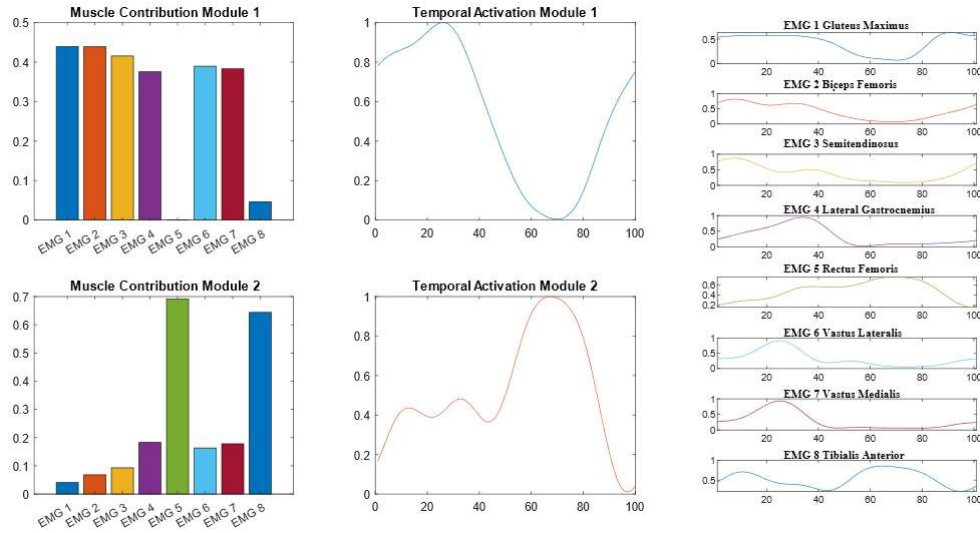


Figure 3. Synergy modules of the maximal velocity phase. On the left, histograms show the muscular contributions of individual muscles to the different synergy modules. In the center, Cartesian diagrams show the temporal activation of the synergy modules. On the right, the EMG signals of individual muscles are displayed.

Synergy module 1 exhibited greater muscular contributions from the GM, BF, ST, GL, VL, and VM muscles. In contrast, synergy module 2 demonstrated a higher muscular contribution from the RF and TA muscles.

The temporal activation patterns of the two modules displayed sequential peaks. Module 1 displayed an initial activation peak from the start of the cycle up to 50%. Module 2 peaked around 90% of the cycle, followed by a second activation peak of module 1 at the end of the running cycle.

Table 1. Cross-correlation analysis

Module of temporal activation during the acceleration phase	Module of temporal activation during the maximal velocity phase	Correlation coefficient	Description
3	2	0.96	Similar
1	1	0.76	Not similar
2	1	0.35	Not similar

Cross-correlation analysis (Table 1) showed a high similarity, with a correlation value of 0.96, between the temporal activation of synergy module 3 during the acceleration phase and the temporal activation of synergy module 2 during the maximal velocity phase. In contrast, there was no similarity between the temporal activations of synergy modules 1 and 2 during the acceleration phase and the temporal activation of synergy module 1 during the maximal velocity phase, with correlation values of 0.76 and 0.35, respectively.

Table 2. Pearson correlation coefficient analysis

Module of muscle contribution during the acceleration	Module of muscle contribution during the maximal velocity phase	Correlation coefficient	Description
3	2	0.99	Similar
1	1	0.46	Not similar
2	1	0.62	Not similar

Pearson correlation coefficient analysis (Table 2) revealed a strong similarity between the muscular contributions of synergy module 3 during the acceleration phase and synergy module 2 during the maximal velocity phase, with a correlation coefficient of 0.99. However, the muscular contributions of synergy module 1 during the acceleration phase and synergy module 1 during the maximal velocity phase were not similar, with a correlation coefficient of 0.46. Similarly, the muscular contributions of synergy module 2 during the acceleration phase and synergy module 1 during the maximal velocity phase were also not similar, with a correlation coefficient of 0.62.

Discussion

The NMF was used to perform muscle synergy analysis, which identified three motor modules that accounted for over 98.51% of the variance in muscle activity during the acceleration phase. During the maximal velocity phase, two motor modules were identified, accounting for over 94.37% of the variance in muscle activity.

An examination of the temporal activation graphs of the three synergy modules during the acceleration phase reveals sequential activation peaks. The first activation peak occurs in synergy module 2, coinciding with the transition from the end of one gait cycle to the beginning of the next, which corresponds to the terminal swing and initial contact phases (Dugan et al., 2005). The primary muscular contributors to this module are the BF, ST, and GM muscles, with secondary contributions from the TA, VL, and VM muscles. During the terminal swing phase, these muscles are responsible for hip extension, which is crucial for proper foot placement under the center of mass. A forward foot strike can generate braking forces that hinder forward motion (Haugen et al., 2019; Dicharry, 2010). During the initial contact phase, the activation of muscles in synergy module 2 contributes to stabilizing the limb by counteracting the high GRFs resulting from impact, which can be as high as 2.2–2.6 times body weight (Dicharry, 2010).

After the initial contact phase, during the propulsion phase, which spans approximately 20%–40% of the gait cycle (Dugan et al., 2005), synergy module 1 becomes the dominant contributor to muscle activation. This module is primarily composed of the GL, VL, VM, GM, and RF muscles, with a minor contribution from the BF muscle. These muscles collectively generate plantar flexion at the ankle, knee extension, and hip extension, producing the propulsive force necessary for forward movement. Therefore, synergy module 1 appears to be responsible for controlling the propulsion phase during acceleration.

During the subsequent initial swing phase, synergy module 3 exhibits its peak activation. This module is predominantly composed of the TA and RF muscles. It is likely that this synergy module coordinates limb advancement during the initial swing phase because the rectus femoris contributes to hip flexion and knee extension, aiding in the forward swing of the limb, while the tibialis anterior dorsiflexes the ankle to prevent the foot from assuming a plantarflexed position.

Upon examining the temporal activation graphs of the two synergy modules extracted during the maximal velocity phase, we observe that module 1, primarily activated by the GM, BF, ST, GL, VL, and VM muscles, similar to module 2 during acceleration, reaches its peak activation between the end of one gait cycle and the start of the next. However, its activation extends beyond the impact absorption phase, encompassing the propulsion phase as well. In contrast, synergy module 2 during the maximal velocity phase exhibits greater contributions from the RF and TA muscles, becoming active during the initial swing phase and fulfilling a similar function to module 3 during the acceleration phase.

These observations suggest that the CNS uses different control strategies for the lower limbs during the acceleration and maximum speed phases of sprinting, supporting our initial hypothesis that the system adopts different self-organizing models to address the unique demands of each phase. Notably, the similarity observed between both the temporal activation patterns and muscular contributions of synergy module 3 during the acceleration phase and synergy module 2 in the maximum speed phase indicates that the system uses the same self-organizing model to control the initial swing phase in both conditions. The observation of a different number of active modules during the entire stance phase, along with their lack of similarity, suggests that this phase is controlled in a different manner between the two conditions. Specifically, it appears that the system uses two separate self-organizing models during acceleration: one dedicated to impact absorption and another for propulsion. In contrast, during maximum speed, a single self-organizing model is used for both absorption and propulsion.

The greater emphasis on the propulsion phase during acceleration, which is essential for rapidly increasing locomotion speed, likely requires a dedicated synergy module for its control. This differs from the maximal velocity phase, where the main goal is to maintain a constant speed rather than generate high anterior–posterior propulsive forces (von Lieres Und Wilkau et al., 2020). Consequently, a single synergy module is sufficient for controlling the entire stance phase during maximal velocity.

Previous studies on muscle synergies during running, which also used NMF, have reported varying numbers of synergy modules, ranging from four to five (Cappellini et al., 2006; Nishida et al., 2017; Santuz et al., 2018; Yokoyama et al., 2016). This discrepancy may be attributed to differences in the number of muscles analyzed, which ranged from twelve to thirty-two in previous studies compared to only eight in this pilot study. Additionally, the specificity of the running task may also contribute to the observed variations. The muscle synergies involved during sprint running, particularly when starting from rest, may differ from those involved in steady-state running under various conditions, such as running on an incline (Saito et al., 2018), uneven surfaces (Santuz et al., 2018), or with different footwear (Santuz et al., 2017).

Furthermore, it is important to note that the previous studies mentioned were performed on a treadmill, which may have influenced their findings. Research has shown that treadmill and overground running differ in their biomechanics and muscle activation patterns (Lindsay, Noakes & McGregor, 2014). Mileti et al. (2020) demonstrated that while the number of muscle synergies extracted during treadmill running and overground

running remained four in both conditions, the activation coefficients (C) differed, with greater regularity observed during treadmill running compared to overground running. This suggests that the use of a treadmill may prompt the CNS to adopt an alternative neural control strategy.

Conclusions

This pilot study demonstrates that the neuromuscular system uses three synergy modules to control the acceleration phase of a sprint and two modules for the maximal velocity phase. This supports our initial hypothesis that the system adapts to the unique demands of each sprint phase using different self-organizing models.

Thus, running seems to be a dynamic task that requires continuous muscle self-organization, with configurations that adapt to the unique demands of each running phase.

While the findings of this pilot study provide valuable insights, they are subject to limitations inherent to such studies, including a small sample size, a lower number of muscles analyzed compared to other studies in the literature, and a limited number of sprints examined. Despite these limitations, the procedures used for identifying foot-contact events to define the running cycle appear to be accurate and reliable. Similarly, the filters applied to process the raw EMG signal, the normalization procedures, the NMF algorithm, and the VAF thresholds used to determine the optimal number of modules have proven to be sensitive and effective in distinguishing the different modes of synergistic control across various muscles and conditions. Therefore, it is considered feasible to apply these procedures to a larger sample to validate the results of this study.

These findings have practical implications for coaches because they can help inform the selection of exercises that optimize training transfer. Future research could also explore how environmental factors influence self-organizing patterns and whether a maximal sprint performed in a controlled environment, such as on a track, differs from a sprint performed in a more dynamic environment, such as on a soccer field.

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Consent to participate: The participants provided informed consent, authorizing their participation in the study.

Data availability statement: Data are available upon request.

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