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Review

How Recent Findings in Electromyographic Analysis and Synergistic Control Can Impact on New Directions for Muscle Synergy Assessment in Sports

Alessandro Scano , Valentina Lanzani and Cristina Brambilla *

Institute of Intelligent Industrial Systems and Technologies for Advanced Manufacturing (STIIMA), Italian Council of National Research (CNR), 20133 Milan, Italy; alessandro.scano@stiima.cnr.it (A.S.); valentina.lanzani@stiima.cnr.it (V.L.)
* Correspondence: cristina.brambilla@stiima.cnr.it

Abstract: Muscle synergy is a state-of-the-art method for quantifying motor control with multichannel electromyographic (EMG) recordings. Muscle synergies have been used in many sports-related applications, including swimming, baseball, basketball, and other sports, for a biomechanical description of sports movements, improving athlete performance, preventing injuries, and promoting synergy-based rehabilitation strategies. However, despite the fact that it is clear that, in many sports, the assessments based on multi-muscle analysis are crucial for performance, the practical impact of muscle synergies on sports practice has been quite limited. Thus, so far, the potential of muscle synergy in sports has been poorly explored. However, recent advancements in synergistic models may strongly impact the understanding of motor control in sports. We identified several margins for improvement, which include novel models and updated algorithms: the separation of the EMG components (phasic and tonic) leading repertoires of synergies for motion and holding posture; the choice of multiple synergistic models (spatial/temporal/time-varying and others); the connection of synergies with the task space and the consequent role of non-linearities; the use of computational models and digital twins; and the fields and sports in which synergies can be applied. In this narrative review, we discuss how the novel findings from the biomedical field may fill the gap in the literature for the extensive use of muscle synergies in sports with several applicative examples.

Keywords: muscle synergies; sports; task space; phasic; tonic; motor control

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1. Introduction

Muscle synergies are state-of-the-art methods available to quantify motor control with multichannel electromyographic (EMG) recordings. Muscle synergies have been applied in many sports, including swimming, baseball, and basketball, with the primary goals of enhancing athletes' performance, analyzing specific sports conditions, preventing injuries, and improving rehabilitation strategies. However, despite the clear importance of muscle synergies for the optimization of performance in many sports, the practical impact on sports practice has been quite limited and, so far, the potential of muscle synergy in sports remains underexplored. The aim of this narrative review is to present the various advancements in synergistic models that come from motor control and the biomedical field in recent years, as they may provide valuable insight and directions for future research, with a potential strong impact on our understanding of motor control in sports [1].

2. Muscle Synergies in Sports So Far

A detailed description of the fields of application of muscle synergies in sports has been provided by Taborri et al. [2]. Even though the method was conceived in the framework of motor control for studying intermuscular coordination, it has now been successfully applied in several sports. Some insights have been achieved, and according to our review, they can be classified into four macro-groups: muscle synergy optimization to improve athlete performance [3], muscle synergy analysis to prevent sports injuries [4], muscle synergy as a tool to introduce targeted muscle rehabilitation in order to reduce recovery time [5], and, finally, the characterization of muscle synergies to describe sport-specific conditions and movements [6]. However, as was recently shown by a review of rehabilitation studies in the medical field [7], we think that the achievements and the impact of the method are still low compared to its potential. In the next sections, the main aims for which muscle synergies have been applied in sports are described.

2.1. Muscle Synergy Optimization to Improve Athlete Performance

In the context of sports, relevant information for athletes and coaches is showing the difference in muscle synergies between elite and beginner athletes and is being used to plan training strategies and optimize performance enhancement programs [3,8]. Indeed, several studies have investigated how the characteristics of motor modules, including the number of synergies, the spatial structure, and temporal coefficients, change according to the athlete's skill levels [3]. This relationship between skill levels and muscle synergies has been investigated in various disciplines, such as badminton [8], Japanese archery [9], swimming [10], and wrestling [3]. Matsunaga et al. discovered differences in muscle synergies extracted by comparing advanced and novice badminton players during a smash shot. Indeed, three and two synergies were extracted from the advanced and novice players, respectively. The synergy responsible for the rotation and inclination of the trunk to the nondominant side to hit a shuttlecock at a higher point was common between both groups, while a second synergy was different for each subject due to the uncontrolled flying of the shuttlecock. The advanced players also showed an additional synergy that maintained control over the body while hitting a strong shot. This synergy was not present in the beginners because their coaches mainly trained the upper limbs to speed up the movement of the arm to hit the ball while neglecting training the coordination of the trunk muscles. Therefore, to improve the performance level of badminton players, it is suggested not only to train the coordination of the forearm muscles but also the trunk muscles [8]. Moreover, Matsunaga et al. investigated motor control in Japanese archery athletes, comparing the modules between an elite and a novice group. Extracting two modules from each of the groups, the first module, which mainly reflects the bilateral erector spinae activity during the first half of the shooting sequence, was shared between the groups. The second module, instead, showed a significant difference between the two groups because the elite group engaged mainly the internal oblique/transversus abdominis to fix the trunk during shooting sequences, while the novice group compensated for the low activity of the internal oblique/transversus abdominis with the strong activation of the muscle placed between the costal margin of the ribs and iliac crest. Indeed, the competitive skills correlated positively with improved posture maintenance. Thus, to enhance the movements and optimize performance, the coaches could implement more trunk stabilization exercises [9].

Instead, to improve breaststroke swimmers' performance, Vaz et al. suggested focusing training sessions on optimizing the temporal aspects of inter-limb coordination. When comparing the muscle coordination of the upper and lower limbs between beginners and elite breaststroke swimmers, although the number and the weight coefficients of the muscle synergies were similar between the two populations, there was a significant backward shift in the second synergy of the beginners compared to that of the elite. This synergy involved the upper limb muscles and was responsible for arm-to-leg coordination differences, so the inter-limb coordination was probably the key for improving the breaststroke performance [10,11]. Finally, another example in which muscle synergies were investigated to improve sports performance was the assessment of the wrestling performance during the execution of the Double-Leg Attack maneuver, comparing elite and sub-elite athletes [3]. Indeed, Beinabajii et al. discovered that elite wrestlers showed a greater degree of intra-group similarity across all three temporal activations with respect to the sub-elite athletes. The elite wrestlers demonstrated a high level of precision and coordination during the execution of the maneuver, while the sub-elite wrestlers exhibited more significant interindividual variability, performing the movement with less precision and needing further enhancement in their muscle coordination. Therefore, specialized training can influence the number, the structure, and the time activation of motor modules and studies on this can suggest coaching strategies, training programs, performance assessments, and technique refinements, in order to improve athletes' competitive skills. However, so far, studies have only highlighted the differences between the muscle synergies of trained athletes and those of beginners, but training programs based on a synergy-based assessment to optimize sports performance have not yet been realized in a real-world scenario.

2.2. Muscle Synergy Analysis to Prevent Sports Injury

Preventing sports injury is a major issue in professional sports. In the literature, it emerged that female athletes suffer a greater number of specific sports-related musculoskeletal injuries than male athletes [12]. For instance, in female basketball players performing the 45° side-step cutting task, the risks of non-contact anterior cruciate ligament injury are significantly higher than those of male basketball athletes, because female athletes exhibit lower hamstring activation and higher quadriceps activation, and this concurrent effect causes an increased risk of anterior cruciate ligament injury [13]. These injuries can result in reduced athletic performance and may also cause additional injuries in other areas of the body. Therefore, identifying posture control strategies and analyzing muscle synergies recruited during females' movements could help to decrease the potential risk of injuries [13,14]. Indeed, Kim et al., comparing elite hockey athletes and non-athletes, identified, in the elite athletes, specific muscle synergies exploited to restore balance against unexpected external perturbation, which could be used as an instrument to develop a training strategy for female athletes requiring high postural stability to lower their risk of injuries [14].

Another factor that may increase the risk of injury is fatigue, as it leads to impairments in functionality and can alter the kinematics of movements. These changes in kinematics could derive from adaptations occurring at the neuromuscular level [4]. To better understand how the central nervous system (CNS) develops neuromuscular strategies in response to fatigue, Thomas et al. applied an external rotation (ER) fatigue protocol on competitive baseball players to mimic the fatigue during repetitive overhead throwing. This study aimed to determine the effects of isolated ER fatigue on the adaptation of muscle synergies in the shoulders of baseball players in order to help clinicians develop injury prevention plans limiting fatigue to decrease overuse-related injury rates. This study discovered a reduction in the variance accounted for (VAF) in ER movements and abduction movements, and a change in muscular weights before and after fatigue. These changes may be evidence that the CNS simultaneously seeks a compensatory response to continue the desired movement, maintaining muscle force output, but at the same time, tries to reduce the risk of injury [4]. Therefore, it is needed to delay or avoid the ER fatigue that induces neuromuscular changes to reduce the risk of injury. To achieve this purpose, the optimal treatment strategy is muscular endurance training of the external rotators, as Moore et al. demonstrated that high school-aged baseball players increased their posterior shoulder endurance by completing a 20-week training program [15].

Thus, in general, the differences found between muscle synergies in several conditions or subjects could be a signal for understanding how to intervene in order to prevent/reduce the risk of injury.

2.3. Study of Muscle Synergies to Improve Rehabilitation Strategies

The high incidence rates and prevalence of injuries in professional and elite athletes show the need to find new rehabilitation strategies to achieve faster and more effective recovery. Several studies analyzed muscle synergies to investigate muscle coordination in order to understand how to improve the rehabilitation process following sports-related injuries [5,16,17]. Matsuura et al. compared two groups of swimmers: swimmers without injury (control group) and swimmers with shoulder pain (swimmer's shoulder group). They discovered that the active synergy in the early pull phase showed a higher activation of the pectoralis major (PM) and a lower contribution of the rectus femoris (RF) in the control group than in the swimmer's shoulder groups. Therefore, while the control group performed the pull motions using the PM, the swimmer's shoulder group compensated for the lack of traction of the PM, gaining propulsion by using lower limb movements. Moreover, they noted that the synergy responsible for the late pull showed a larger contribution of the lower trapezius (LT) for the control group with respect to the swimmer's shoulder group. Indeed, the LT can depress the scapula, allowing the performance of the pull movement, which is avoided in those with swimmer's shoulder. Finally, the synergy that was activated before and after the hand entered the water shows higher upper trapezius (UT) weight for the swimmer's shoulder group than the control group, and this may be precisely the cause of swimmer's shoulder. Thus, each phase of movement requires specific and coordinated muscle activation. Indeed, the proper propulsive force given by linkage between the upper and lower limbs is necessary during the early pull phase, while a high contribution of the LT and a reduction in the involvement of the UT are required in the late pull and at hand entry, respectively. Therefore, it was found that each phase of the rehabilitation process needs the rehabilitation of different target muscles [5].

However, muscle synergies are not only used to identify target muscles to rehabilitate but they have also been applied to develop personalized therapeutic strategies for athletes affected by the yips [17]. The yips is a psycho-neuromuscular disorder that is characterized by involuntary movements interfering with the automatic execution of fine movements. Muscle coordination is necessary for sports movements and the mechanisms of impairment in athletes with the yips remain unknown. Aoyama et al. tried to assess the spatiotemporal muscle coordination in baseball players while throwing, comparing healthy baseball athletes and athletes with the yips. They discovered that only the athletes presenting dystonic symptoms during the throwing execution exhibited specific spatiotemporal patterns of muscle synergies that differed from those in the control players, while when symptoms were not reproduced, muscle synergies were not impaired. Therefore, muscle synergy analysis can help to identify the characteristics of muscle coordination in players who show dystonic symptoms and can be useful for developing personalized therapeutic treatments, depending on the individual characteristics of the yips symptoms in order to try to resolve athlete-specific situations [17].

Instead, Severini et al. employed a synergy analysis to validate a recent rehabilitation protocol for hamstring injury to verify if it was more effective than traditional treatments [16]. Since hamstring injuries are very frequent, they tried to characterize the neuromechanical profile of the exercises of an alternative eccentric training protocol for hamstring muscle injuries (L-protocol) defined by Askling et al. [18]. This protocol consists of three eccentric exercises that load the hamstring muscle during extensive lengthening. In this study, muscle synergies are used to derive an easily understandable index of functional co-activation of the four muscles. The results showed that during the different exercises of the protocol, the hamstring muscles are passively stretched or actively eccentrically contracted to stabilize the body and resist hip flexion. Moreover, they are recruited in co-activation modules that can have different functional roles, either driving or stabilizing the movement depending on the exercise performed. In conclusion, the L-protocol is composed of three different exercises that elicit different beneficial effects in the hamstring and reduce the time to return to sport after hamstring muscle injuries when compared to a more "traditional" exercise-based rehabilitation protocol. Therefore, the L-protocol may be used in the future as a new effective strategy to improve recovery after a hamstring injury [16].

In conclusion, muscle synergy analysis may be useful to develop or validate new rehabilitation strategies that are athlete-specific to achieve targeted recovery of injured muscle.

2.4. Muscle Synergy Characterization Based on Sport-Specific Conditions

For some sports, muscle synergies are influenced by the type and level of exercise [6]. Muscle synergies exhibit inter-subject variability due to motor skills and training related to subject-specific motor patterns [6,19], even though they remain similar when considering different mechanical conditions [19]. Indeed, comparing skateboard tricks, Kaufmann et al. showed that the different tricks performed by skateboarders have the same motor complexity because the number of synergies required did not change, but the synergies extracted from each trick were different in composition, as each trick shared few synergies with the others but included several task-specific synergies. This mechanism underlies how athletes learn new movements. Indeed, it was hypothesized that during the acquisition of a new skill, the synergies responsible for "basic movement" remained unchanged, while only some synergies account for movement fine-tuning and can be newly formed [6]. On the contrary, analyzing healthy cyclists who performed three cycling tasks over a range of rotational speeds and resistant torques, Esmaeili et al. showed that muscle synergies were similar across all mechanical conditions. Therefore, subjects who perform different mechanical conditions use the same motor control strategies for cycling [19].

Instead, when the inter-subject variability is considered, both studies showed that the muscle synergy structure can change from subject to subject. Indeed, Kaufmann et al. analyzed the inter-subject variability, comparing skateboarders, and found that the variability between subjects was very high and this was caused by the freedom with which the same exercises could be performed. Each athlete could have multiple solutions to achieve a goal and only the fundamental movements were the same. Therefore, since, in this sport, there are no stereotyped movements, workouts are based on many repetitions of each movement to refine techniques, but each athlete is free to adopt specific strategies to achieve a goal [6]. Esmaeili et al. noted that, despite the muscle synergy similarity across the mechanical conditions, the individual synergy vectors and coefficients across the subjects were, in some cases, more variable. These differences may be due to the subject-specific motion pattern depending on the motor skills and training of the cyclist [19].

Therefore, these findings could help us understand how motor strategies are exploited to learn a sport or a specific task, and which motor strategies are used to reach specific goals.

3. Muscle Synergies in Sports: Limitations

In our screening of the literature, we noted that in sports, muscle synergies have been used not only to cluster and categorize athletes, as is carried out usually in the medical field with patients, where synergies are mainly used as biomarkers [7,20], but also for practical aims such as to reduce the risk of injuries, to maximize the effect of training, and to induce better performance. On the other hand, sports applications suffer from several methodological limitations, as many advanced methods available for biomedical synergistic modeling and patient characterization have not been employed in the sports context. This limitation has reduced the potential of muscle synergies and partially prevented the method from being extensively used in sports practice. The limitations can be divided into two groups: first, some of them are inherent to the method and intrinsically hard to overcome; the second group of limitations instead can be faced by exploiting recent findings in motor control and represent the focus of this contribution.

3.1. Limitations Inherent to the Method

In this section, the limitations strictly inherent to the method and the present state of technology include the following:

Device price. Multichannel EMG has a cost that might make it not applicable or sustainable in some contexts.

Device encumbrance. Applying multichannel EMG requires time-consuming procedures; moreover, applying many sensors may reduce the transparency of the measurement and this issue must be taken into consideration for some applications.

Dedicated personnel. Professionals with technical knowledge are needed for applying the EMG technology, performing the analyses, and correctly interpreting the results. In some contexts, this might require additional personnel or specific training.

3.2. Methodological Limitations

In this section, a specific list of the limitations that apply to the studies conducted so far when using muscle synergies is provided. They are also summarized in Table 1.

Synergies extracted using the spatial model only. So far, only Non-negative Matrix Factorization (NMF- based approaches [21] based on the spatial model have been used. While this is not a limitation "per se", this approach limits the interpretative potential of synergistic approaches, as several other available models could capture specific features not emphasized with the spatial model [22].

Synergies used mainly for evaluation. The vast majority of the available studies used muscle synergies only to provide a picture of the motor control available to athletes at a given stage [5]. However, as preliminarily suggested by some studies, synergies might "enter the loop" of training, rehabilitation, and injury prevention by providing decisional elements rather than descriptive analysis only [13].

Synergies used to examine the neural drive only. The standard formulation of muscle synergies covers only neural variables derived from surface EMG. This makes it not trivial to map EMG activations to the motor output, the so-called "task space", limiting their range of application and interpretation.

Synergies extracted without using non-linear models. The synergy theory assumes a linear combination of synergies. This assertion is supported by findings on animals and humans. However, especially when combining synergies with task space variables, non-linear relationships might be expected and tools for modeling such non-linear relationships might be needed [23].

Synergies not extracted on separated EMG components. Recent studies have demonstrated that phasic and tonic synergies, associated with motion-related and postural/anti-gravity components, respectively, are different in composition [24]. Thus, separating synergies that originate from these two components might lead to more refined models and a deeper understanding of the biomechanics of gestures.

Synergies not extracted from simulations. While using experimental data allows us to work on real data, a more extended use of models and simulations would allow us to test conditions that are hard to reproduce experimentally and extend the range of the investigations, for example, by incorporating more muscles in the analysis [25].

Synergies extracted in a few fields of application. Many popular sports have never been tested in the framework of muscle synergies, thus providing many opportunities for further investigations.

Table 1. Limitations of the systematic application of muscle synergies in sports and suggestions on how to explore novel directions in the field.

Limitation	Suggestion
Synergies extracted using the spatial model only	To extend synergistic models to spatial, temporal, and spatiotemporal models (and more) [22]
Synergies used mainly for evaluation	To incorporate synergies in extensive training and rehabilitation protocols [13]
Synergies used to examine the neural drive only	To incorporate task variables into synergistic models
Synergies extracted without using non-linear models	To incorporate non-linear models [23]
Synergies not extracted on separated EMG components	To separate phasic and tonic EMG components and extract phasic and tonic synergies (when applicable) [24]
Synergies not extracted from simulations	To promote the use of simulations and digital twins [25]
Synergies extracted in a few fields of application	To expand the range of applications, especially to sports not analyzed yet

The suggestions outlined in the table represent advancements achieved in the application of synergies within the biomedical field. The novelty of this review is to propose the application of these advancements also in sports where the application of synergy analysis is limited. Indeed, extending the application of muscle synergies with the suggested approaches and techniques in sports may support these valuable processes:

- To understand in a more refined way the biomechanical processes that underlie movement.
- To impact on injury preventions: Promoting the use of simulations and digital twins, it would be possible to simulate some load or fatigue conditions to see if they induce joint lesions. In this way, coaches could organize the correct training suitable for their athletes, avoiding injuries during the year.
- To enhance the athlete's performance: Incorporating task variables into synergistic models and using different models to extract muscle synergies, coaches could understand which muscles are activated in the different phases of a gesture and how the activation changes in several training conditions. They could exploit this information to prepare specific training to improve the performance of gestures that require complex sequences of movements.
- To accelerate recovery time: this is useful introducing synergies in rehabilitation protocols to create customized programs to achieve the targeted recovery of injured muscles.

Therefore, extending these novel findings to sports applications may help to reach new goals in different areas of sports.

4. Discussion

Muscle Synergies in Sports: How to Explore New Directions

Regarding the methodological limitations described in this review, we identified several margins for improvement. In this perspective, we discuss several applicative examples of how the novel findings from the biomedical field may fill the gap for the extensive use of muscle synergies in sports.

Extending synergistic models to spatial, temporal, and spatiotemporal models (and more). In all the studies examined in the literature, the standard spatial model based on NMF was employed. Given a set of n muscles, including t tasks, with r repetitions, resampled with s samples each, and denoting as w the number of extracted synergies, the spatial synergy model decomposes the *EMG matrix* $[n \times (t{\cdot}r{\cdot}s)]$ into the product of the synergy matrix W $[n \times w]$ and the temporal coefficients c $[w \times (t{\cdot}r{\cdot}s)]$. However, other models are available that capture the regularities found at the temporal level. The temporal synergies break down the movement sequence to capture essential details about the starting and ending postures, as well as the brief forces needed to speed up or slow down the body as it moves toward the target [26]. Therefore, temporal synergies might be used to analyze movements that have a well-defined and repeated phase because they allow one to highlight modifications in muscle activations induced by speed or power changes. A typical case in which a temporal model might be effective is when cyclic movement with a precise temporization is analyzed, such as cycling or swimming. Indeed, these two sports provide cyclic movement with well-defined phases, and in each phase, the same muscle groups are always activated. Therefore, using temporal muscle synergies, it is possible to identify in which phase muscles would be activated to ensure the efficiency of movements and how muscle activation changes if the training conditions change.

Incorporating synergies in extensive training and rehabilitation protocols. In other fields such as rehabilitation, since the preliminary studies from Cheung et al. [20], synergies have been used mainly as biomarkers for quantifying the level of disability. Interestingly, in rehabilitation, there are no available studies that use synergies as tools for customizing and modifying therapies or conceiving specific therapeutic paths [7]. On the contrary, even though, in sports, synergies have been used merely as an evaluation method, there are preliminary studies that suggest the use of synergies to customize the rehabilitative intervention after injuries [5], to reduce the risk of injury [14], and to optimize athletes' performance [8]. These lines of research are precious and should be fostered as they would allow us to move from pure academic research to useful practical knowledge and for customizing training. One valuable option, in this view, is to incorporate task variables into synergistic models.

Incorporating task variables into synergistic models. When motor synergies are used, proper interneural and motor–neural networks are elicited, and motor commands are recorded through EMG. Thus, muscle synergies are purely an expression of such parameters. Recent lines of research, as highlighted in Alessandro et al. [27], suggest that a more comprehensive perspective on the understanding of synergies would be unveiled when we understand the link with the task space, incorporating synergistic models with a description of the motor correlates generated with muscle synergies. So far, a first approach has been proposed by Ting et al., who investigated the link between muscle synergies and endpoint force during postural control because maintaining balance is a force control task [28]. Therefore, they tried to develop muscular–kinetic synergies extracted with NMF considering both muscular and force signals in order to better explain the correspondence between synergies and whole limb force. More recently, the traditional NMF algorithm was extended to produce Mixed Matrix Factorization (MMF), a novel factorization method that incorporates any kind of unconstrained variable into the factorization [29]. The method was conceived to mathematically support the new notion of "kinematic–muscular synergies", that needed to allow the factorization of variables that could either be positive (when a joint is flexed) or negative (when a joint is extended). Kinematic–muscular synergies provide a biomechanically oriented characterization of motor control as they incorporate both the muscular activation and the functional joint output [30]. Another attempt comes from the work of Delis' group [31], who use information theory to describe how multichannel EMG relates to task space variables.

Incorporating task space variables might result in a major step toward the applicability of muscle synergies to sport, as each neural activation would be linked directly to the motor outcomes they produce, providing a versatile tool potentially applicable to performance optimization, understanding of risks of injury, rehabilitation, and more.

This approach is potentially useful for the analysis of all sports because it allows us to explain better how the neutrally originated synergy weights are linked with motor task performance. In particular, this method could be useful to study movements in sports where it is not easy to assess the biomechanical function of synergies through muscle activation analysis alone. Typical examples may be movements not cyclic in nature, composed of many phases. Some examples might be the high and long jump or the spike gesture in volleyball. Indeed, these sports involve gestures that require complex sequences of movement and/or aggregated multi-task motion, which may largely benefit from task-related synergistic approaches. For example, to perform a high-performance long jump, it is first needed to prepare a good run-up. Therefore, it is important to know which muscles are involved during the run-up, separating them from those involved during the jump deadlift in order to understand which muscle activations are necessary for each gesture phase to achieve an optimal jump performance. Incorporating task variables into synergies would help to segment and quantify properly more complex gestures and could be useful to identify how coaches could train the muscles responsible for the run-up in order to improve muscle activation during the jump and make it more effective. The same concepts can be applied in the volleyball spike because the power and the efficacy of a spike are affected by the correct execution of the three steps before jumping. Adding kinematic and biomechanical information to the synergy composition would make EMG measurements more related to joint motion, paving the way for an increased understanding of sports gestures.

Figure 1 shows an example of kinematic–muscular synergies and their corresponding temporal coefficients during human locomotion. This figure is an original representation and it has been created using data from the gait study by Moreira et al., in which a gait analysis on a subject who performed four steps was executed [32]; the EMG was estimated with a biomechanical simulation and its envelope was used as input for the MMF algorithm in order to extract the spatial kinematic–muscular synergies [30]. In these synergies, both the muscle activations and the joint activities were highlighted. W1 shows the activity of the psoas, adductor, gastrocnemii, and soleus associated with ankle plantar flexion and the flexion of the knee and hip and activates at the end of the stance phase during the propulsion. W2 shows the glutei, biceps femoris, and rectus femoris activated at the beginning and the end of the gait cycle for flexing the knee and hip. W3 is predominantly muscular with the semitendinosus, semimembranosus, vastus medialis, and lateralis activated during the stance phase. W4 associates the knee and hip extension to the rectus femoris during the swing phase. Finally, in W5, the hamstring muscles are related to knee and hip extension at the beginning of the early stance and the beginning of the swing phase. Therefore, using kinematic–muscular synergies, it could be clearer to understand the link between muscle activation and biomechanical function.

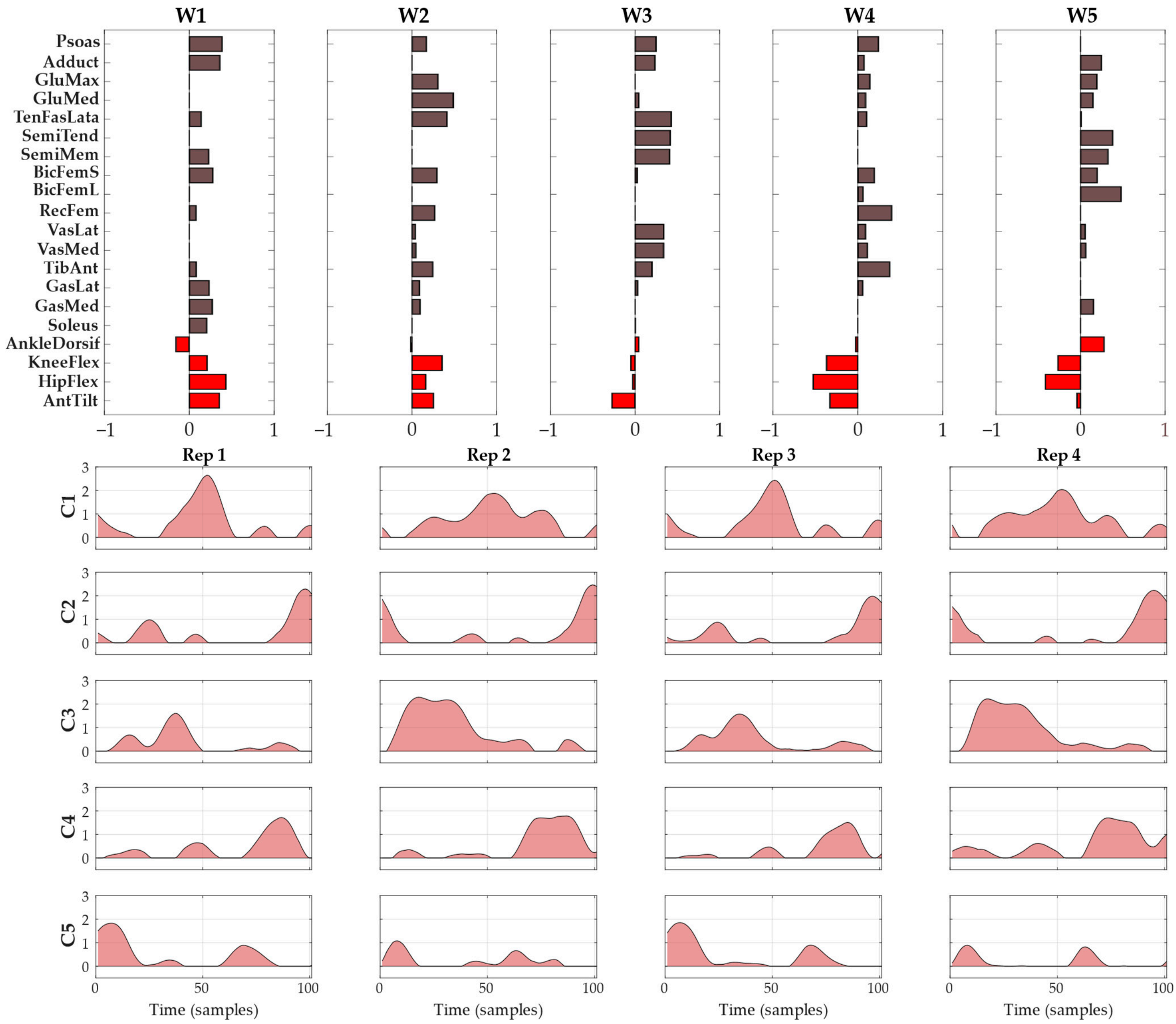

Figure 1. The figure is an original representation created with the data from a study by Moreira et al. [32] and Lanzani et al. [30]. Kinematic–muscular synergies from locomotion in four strides are shown at the top of the figure, and below, the corresponding temporal coefficients are portrayed. In kinematic–muscular synergies, the muscular part is in gray and it highlights the muscle activations, while the kinematic part is red and it shows the corresponding joint acceleration.

Incorporating non-linear models. Preliminary work on muscle synergies [33,34] showed that synergies combine linearly, and, thus, linear models should effectively capture their combination to produce movement. Most of the available corpus of the scientific literature has built on these bases and NMF has become the reference algorithm for the field [23,35]. However, the dynamics of the neuromusculoskeletal apparatus contain several levels of non-linearity, and the task space variables might be related to muscle synergies with non-linear models. Thus, future work will have to consider the adoption of non-linear models to capture such relationships, for example, using autoencoder neural networks.

Separating phasic and tonic EMG components. Phasic and tonic EMG relate to motion-related and postural or anti-gravity EMG components, respectively. Since the first studies from Flanders [36,37], few studies in motor control have addressed the need to separate such components, especially in upper limb movements [38], and in a recent work, it was demonstrated that the collection of synergies underlying phasic and tonic EMG are in principle different, sharing few synergies only [24]. Thus, separating the two components may shed light on the understanding of sports gestures, especially when the upper limbs are involved in anti-gravity movements. In Figure 2, the two components are shown in a typical reaching movement of the upper limb to reach a target. It can be seen that the phasic EMG shows a typical biphasic burst structure, accounting for the acceleration and deceleration of the limb, while the tonic EMG can be modeled with a linear ramp that connects the baseline EMG level before and after movement onset/offset. The EMG data used to create Figure 2 were derived from a dataset presented in Scano et al. published in 2019 [39].

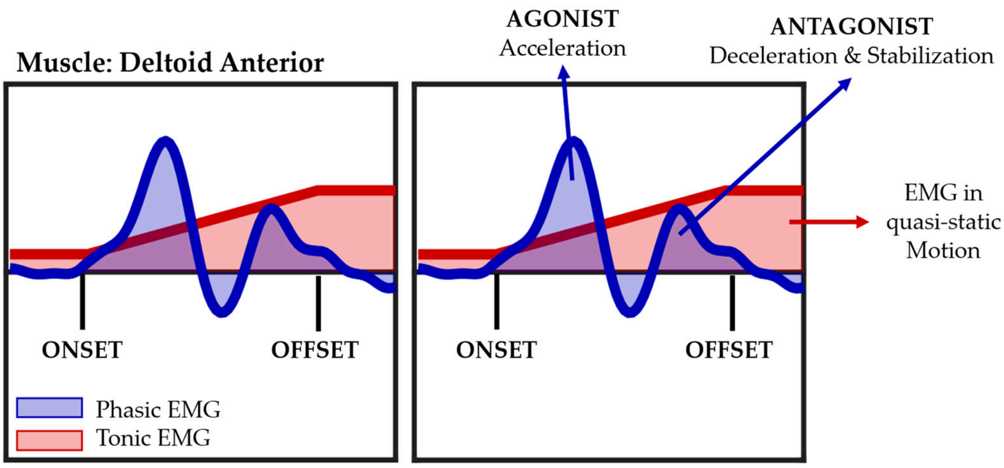

Figure 2. Phasic (blue) and tonic (red) EMG of the anterior deltoid during a reaching movement of the upper limb towards a target. This EMG data were derived from a dataset presented in an upper limb study published in 2019 by Scano et al. [39]. The kinematic onset and offset of the movements are shown as well as the two components in which the EMG can be divided. Phasic EMG showed a typical biphasic burst structure, accounting for acceleration and deceleration, respectively, while tonic EMG is modeled with a linear ramp that connects the baseline EMG level before and after movement onset/offset.

The separation of the EMG components allows for a more precise analysis of the different roles played by muscles within the movement. Moreover, this separation allows us also to investigate the role of the negative phasic EMG components that may give insight into efficient movement execution during sports movements when exploiting gravity [40]. In particular, for many sports gestures, it becomes possible to divide the movement preparation phase, where tonic EMG plays a major role, from the movement execution phase, in which phasic EMG also comes into play, enabling the acceleration and deceleration of the arm. Postural control is recruited to prepare an efficient movement execution by coordinating the body to counteract gravity; moreover, such tonic EMG components are modulated during movement execution to guarantee support even when the phasic components start to act. There are some sports, such as tennis and basketball, in which maintaining control of posture to assume the correct body position before the execution of the movement is critical to being able to complete the desired movement successfully. Therefore, it is important to study in depth the static position by analyzing the tonic EMG and then how the transition from static position to movement performance occurs.

To hit a tennis ball powerfully, for example, it is fundamental to assume the correct body position before the shot because it is essential to properly transfer the body weight and to guarantee a good balance. The tennis player must position his feet to rotate his hips and bring his arm back by rotating his shoulders, ensuring the proper alignment of the hips and shoulders. This process allows a player to accumulate the necessary energy and release it efficiently, striking the ball with power. The positioning time is very short, but it is important to understand how the muscle contraction acts at that instant to prepare the body to see if the shot will be efficient. Therefore, in this case, the EMG phasic component is dominant because it allows the athlete to perform a rapid movement, but its progression and the height of its burst are highly dependent on the action of the tonic component. Separating the phasic and tonic EMG could lead to a more detailed assessment and understanding of the gesture, as clearly shown in Figure 3, when using upper limb data that were derived from the study published by Scano et al. in 2019 [39].

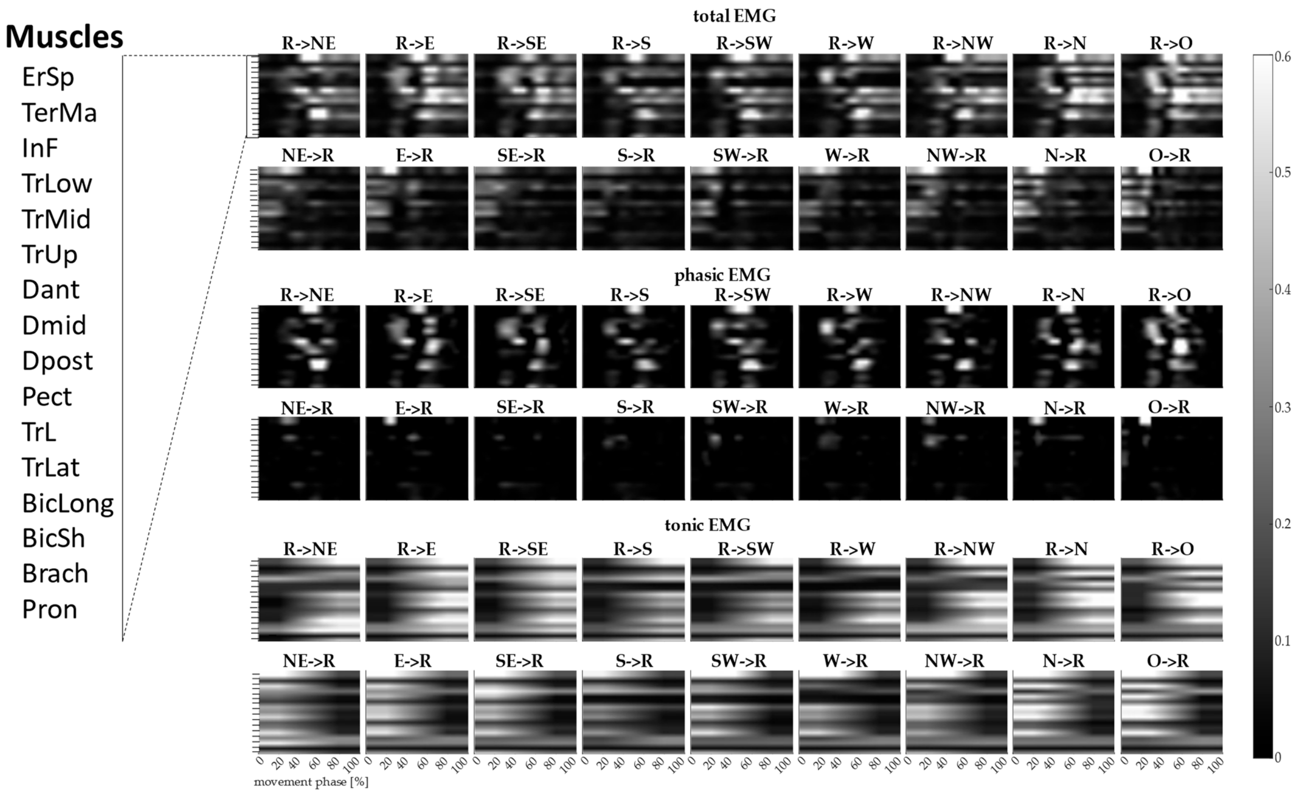

Figure 3. This figure is an original representation created using the upper limb EMG data presented in Scano et al. [39]. A gray-scale colormap portrays the magnitude of total EMG, phasic EMG, and tonic EMG for upper limb movements when aiming at different targets in the upper limb workspace, showing the very different structure of motion-related and posture EMG components. The muscles analyzed are as follows: erector spinae (ErSp), teres major (TerMa), infraspinatus (InF), lower trapezius (TrLow), middle trapezius (TrMid), upper trapezius (TrUp), anterior deltoid (Dant), middle deltoid (Dmid), posterior deltoid (Dpost), pectoralis (Pect), triceps long head (TrL), triceps lateral head (TrLat), biceps long head (BicLong), biceps short head (BicSh), brachioradialis (Brach), pronator teres (Pron).

Moreover, considering also basketball, the separation of the two components may help to shed light on the understanding of the biomechanics of shooting for a basket. Indeed, it has been noted that to be able to make a basket, is important to bend the legs and hips slightly to build up the necessary power while maintaining good stability and balance, and to bend the elbows and wrists to direct the ball towards the basket. As the position before the shot is essential to reach the goal, the EMG tonic component has a primary role, while the phasic component is secondary. Indeed, since the shot involves maintaining a correct position, the phasic component acts only at the end to allow the execution of the shot quickly and precisely.

A summary of innovative approaches for synergistic control at an algorithmic level is shown in Figure 4. A description of possible innovative lines of action for future research follows.

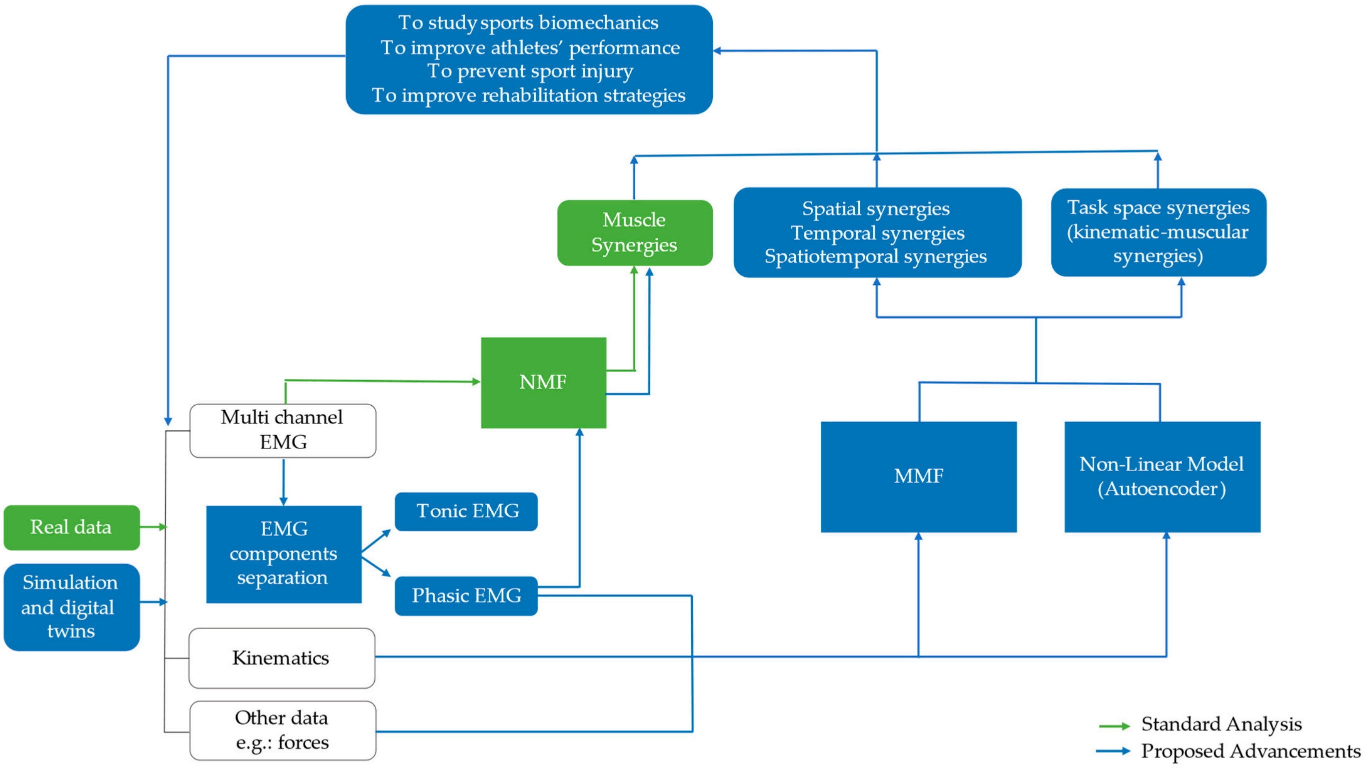

Figure 4. A schematic of how standard muscle synergy analysis could be enhanced with recent findings. Standard synergy analysis is usually performed with the NMF algorithm (mainly the spatial or temporal model); the green path of the scheme follows the main lines of research applied so far in sports; it is not comprehensive for all the models available and it provides mainly a picture of the motor control of athletes at a given stage. The proposed approaches (blue path) suggest separating phasic and tonic components and extracting kinematic–muscular synergies, muscle synergies with negative components, and functional synergies that might be crucial for the better application of synergistic approaches in sports, such as to create rehabilitation protocols or suitable training programs customized for athletes.

Promoting the use of simulations and digital twins. There are many tools available that can be used to simulate biomechanics and may impact provisional models capable of improving the understanding of specific sports gestures. Interestingly, some of them may allow us to model many muscles and to apply muscle synergies more comprehensively. It was shown in recent studies that experimental models may neglect some synergies, as only a few muscles are observed [25]. Therefore, simulations and digital twins could provide a more complete picture of a subject's motor control. Moreover, using simulations and digital twins may be very useful in sports applications because it is possible to simulate load or fatigue conditions that could cause injury during performance. In this way, using this information, coaches may prepare balanced training programs to prevent injury during the sport's season. Alternatively, using these models, experimenters could modify specific biomechanical variables to assess whether movements or athletic gestures improve. This approach would enable coaches to design targeted training programs aimed at altering these biomechanical variables, either to optimize movement execution or to facilitate rehabilitation following an injury. The limitations of this instrument are the time required to simulate a lot of conditions and the need to have experts who know how to use these simulation models and interpret the results obtained.

Expanding the range of applications, especially to sports not analyzed yet. Even though there is already some literature available, the use of muscle synergies in sports is still quite marginal, especially when considering the practical impact achieved on generating novel training protocols, the improvement of technical gestures, injury prevention, and recovery after injuries. However, considering the limitations of standard approaches based on muscle synergies, many useful applications have already been identified, and several more might be added. Our screening for this contribution revealed that athletes from many popular sports including soccer, volleyball, tennis, and some martial arts, have never been analyzed in the framework of muscle synergies, missing the opportunity to increase the range of applications of this method.

Another sporting environment underrepresented in the field of muscle synergies is the Paralympic sport where the application of muscle synergy methods to study motor control is still limited. In Paralympic athletes, EMG was measured to evaluate the start of muscle activation and to calculate the co-activation index in order to analyze how muscles work together to stabilize the joints and promote motor control [41]. To achieve a more accurate view of how muscles are effectively activated to perform a movement and to obtain more information about the central organization of motor strategies, it could be helpful to extract muscle synergies also for studying an athlete's Paralympic movement, for example, when orthoses are used.

Motor control information travels from the CNS to the musculoskeletal system through the spinal cord and muscle synergies are some primitive modules that allow the spinal cord to send the information needed for coordinated muscle activation [35,42]. A spinal cord injury alters the conduction of motor and sensory signals across the sites of the lesion, modifying the performance of movements. Therefore, in athletes with spinal cord injury, motor control is impaired, and it would be interesting to shed light on how muscle synergies are modified so that multi-muscle movements can still be performed effectively [42].

Comparing the muscle synergies of non-disabled experienced athletes with those of Paralympic athletes could be a valuable method for understanding the motor control mechanisms adopted by individuals affected by movement disorders and compensatory strategies. Indeed, for example, comparing the muscle synergies of two archers with and without disability during the different phases of shooting, Vendrame et al. discovered the compensatory strategies adopted by the athletes with disability, such as the BI activation during the pulling of the bowstring or the involvement of the UT for supporting the bow weight throughout the shooting gesture [43]. Following this study, coaches could use muscle synergy analysis as a tool for understanding the compensatory strategies implemented by Paralympic athletes to optimize their skills and maximize their performance.

5. Conclusions

This narrative review presented several examples of how muscle synergies have been exploited to enhance various aspects of sports, including injury prevention and the development of innovative training programs aimed at optimizing athletic performance. However, these applications remain limited, and more advanced algorithms are needed to fully understand synergistic control.

As discussed, the most suitable synergistic model for studying motor control should clearly link muscle activation to motor tasks performed while further approaches may also account for the non-linear characteristics of the neuromusculoskeletal system. In the field of biomedical research, advancements have been made in algorithm development following this direction, but these new algorithms still have limited applications in other fields, such as sports.

However, sports provide an excellent domain for exploring synergies, as every sporting gesture requires the activation of specific muscles at a precise moment, which is exactly the kind of dynamics that can be studied through synergy analysis. In this review, we presented several synergy-based methods that we hope will become the state of the art in advancing sports applications. Furthermore, we believe that the application of muscle synergies in sports should adopt the same level of precision applied in the biomedical field in order to fully harness the potential applications of muscle synergies.

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