Faculty of Physical Culture

Palacký University Olomouc

Dissertation Thesis

Biomechanical Factors Contributing to the Volleyball Spikes Success Rate among Young Elite Volleyball Players

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To my dad,

For his advices, his patience, and his love

Because he understood.

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Abstract

Success rate in volleyball spike is directly linked to the attacking capacities of volleyball players. Generally, several biomechanical parameters (i.e., approach speed, jump height, etc.) are highlighted as the key elements in the spike success rate. Nevertheless, a lack precise information about the principal contributors to the volleyball spike success rate exists in the literature. Thus, this study investigated the kinematics and kinetics of volleyball spike performance using linear (discrete data) and non-linear (neural network) approaches to explore the main contributors to the volleyball spike success rate among young elite volleyball players. Although the spike jump heights could pave the way for a successful spike performance (via increment of point of view over the opponents' court), it is the upper limb velocities, particularly hand velocity, that plays a pivotal role in spike success rate. Basically, after reaching to the minimum required jump heights, it is a coordinated action of upper limb segments, which aids in spike velocities, that provides the attackers with the opportunity to direct the ball with greater chance of success.

Keywords: Kinematics, Self-Organising Map, Kinetics, Volleyball, 3D Analysis.

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1 Introduction

1.1 Volleyball spike: the theory and contributory factors to it

Volleyball spike is “a means for attacking to opponents’ playground over the net” by the middle-blockers, wing-spikers, and opposite-spikers, while opponents try to encounter (block) them (H. Wagner et al., 2014). Spikes are the second and the primary attacking tool to score a point in volleyball. All players, except the libero, could perform volleyball spikes to attack. According to the international volleyball federation (FIVB) official rules, only those players who play in positions number 2, 3, and 4 could attack within the first 3 meters of the playground (figure 1). Nevertheless, attacking from behind the first 3 meters’ line is permitted for wing and opposite-spikers those who play in 1, 6, and 5 positions. Adopted strategies to hit the ball is different among the players, as the middle-spikers attack in the closer distance to the setters (mostly at the centre) and hit the 0.5-1m over-the-net sets (passes), while the wing- and opposite-spikers attack from both sides and hit longer (over 1m height) sets.

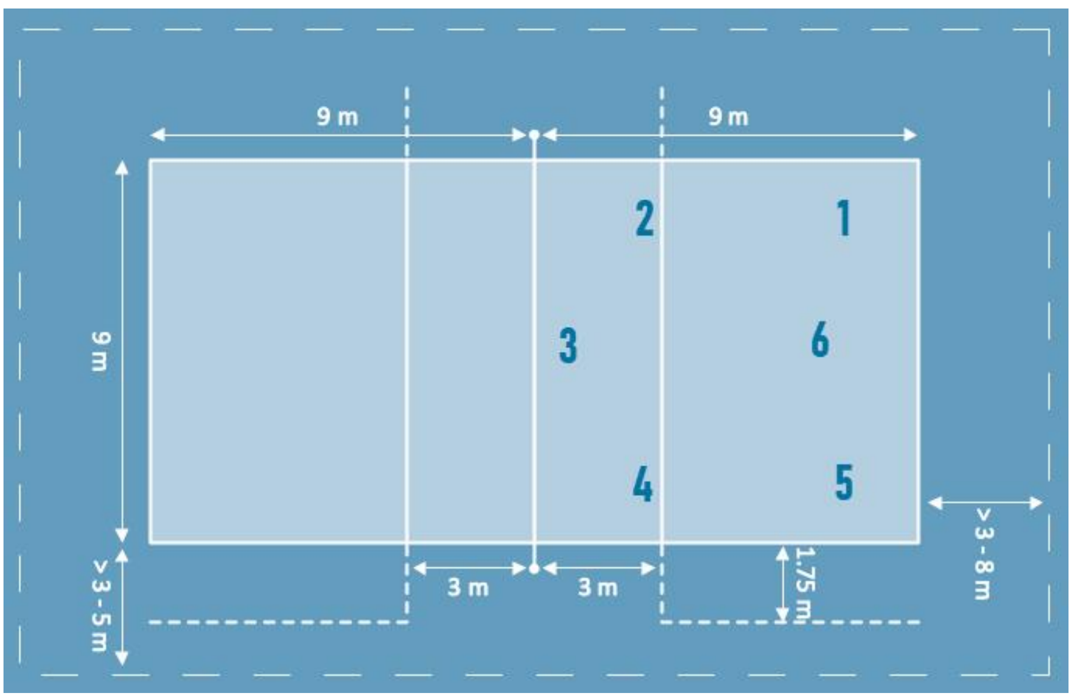

Figure 1. Volleyball playground and schematic positions of the players at each turn.

Volleyball skills, spikes in particular, are one of the top five most practiced skiless in the world (Oliveira et al., 2020). High-skilled volleyball players (those who play at national and international levels) annually perform over 40,000 volleyball spikes (Serrien et al., 2016a). The success rate in volleyball competitions is directly linked to the spike success of the attackers (Fuchs, Menzel, et al., 2019; Valadés et al., 2016). Several physical (i.e., strength levels) and psychological (i.e., stress levels) variables could alter the spike success rate among the attackers (Oliveira et al., 2020; Sattler et al., 2015). Coordinated movement of lower- and upper-limbs is the main contributor to the accomplishment of a successful spike performance (Marquez et al., 2011; H. Wagner et al., 2009). Spike height, jump height, spike velocity and spike accuracy play a pivotal role in spike success rate (Fuchs, Fusco, et al., 2019; Fuchs, Menzel, et al., 2019). Reaching to the maximum possible spike|jump heights and spike velocity is in demands of highly-coordinated movements of distal-proximal-distal segments (through lower-extremities to the pelvis, trunk, and upper-extremities) (Serrien et al., 2018; H. Wagner et al., 2009). Besides, advanced oculi-neuromuscular coordination is required for a successful spike performance, as the attackers must track the ball trajectory using their central vision (Oliveira et al., 2020).

With all the above-mentioned facts in mind, the effects of blocks on success rates could not be ignored. Over 70% of spikes are being blocked by at least two blockers in international competitions (Afonso et al., 2005). The front-block (over the net) is the first and most effective defence strategy that teams have to adopt to encounter the opponent attackers. To this effect, in addition to the prediction of ball trajectory and speed, the attackers must consider the position of the block (using their peripheral vision) to hit the ball accurately towards the opponents' playground.

Several methodological approaches have been adopted to investigate the movement coordination through human movements (i.e., linear methods such as Discrete|Continuous relative phase (DRP|CRP) and Vector coding (VC), and non-linear methods such as Self-Organising-Maps (SOM)) (Needham et al., 2014; Sarvestan et al., 2020; Serrien et al., 2016b). DRP, CRP and VC approaches are generally used to compare the phase angles between two selected joints or segments throughout a discrete or continuous movement (Needham et al., 2014). Although DRP, CRP and VC methods have been abundantly used to analyze human movement, SOMs could provide us with general, but detailed information regarding the coordination of a system as a whole. SOM is a class of artificial neural networks (unsupervised machine learning) that identifies complex patterns in various multi-dimensional sports activities (Serrien et al., 2017).

Overall, volleyball spike is an advanced technique that triggers the oculi-neuromuscular system's coordination for less than 2 seconds in order to score a point. Nevertheless, the coordination patterning of body segments during successful and faulty spikes has not been investigated, to our knowledge. Hence, a precise investigation through the coordination patterning of the successful and faulty spike could reveal performance deficits leading to errors in volleyball spike. Throughout the next section, the overview of current knowledge and insights concerning the parameters affecting success rate in the volleyball spike performance will be covered.

1.1.1 Volleyball spike phases

As highlighted above, volleyball spike is an advanced technique that consisted of three main phases: approach, plant, and jump (figure 2) (Fuchs, Menzel, et al., 2019). In this study, we ignored the landing phase as we focused on the spike performance till the ball-hitting moment. Starting by approach phase, attackers try to increase the horizontal speed before reaching the plant phase, which is the main aim of this phase. This horizontal velocity greately helps in increment of vertical velocities, after it transformed to the vertical momentum using stretch-shortening cycle (SSC, will be discussed later) of the ankle plantarflexors, knee extensors and hip extensors (Carroll et al., 2019). Besides the lower limb impact on obtaining the peak horizontal velocities during approach, the role of arm swing must not be underestimated. Although the main effect of arm swing is observed in the plant phase (till take-off), it principally starts in the approach phase, and aid in greater horizontal velocities (H. Wagner et al., 2009).

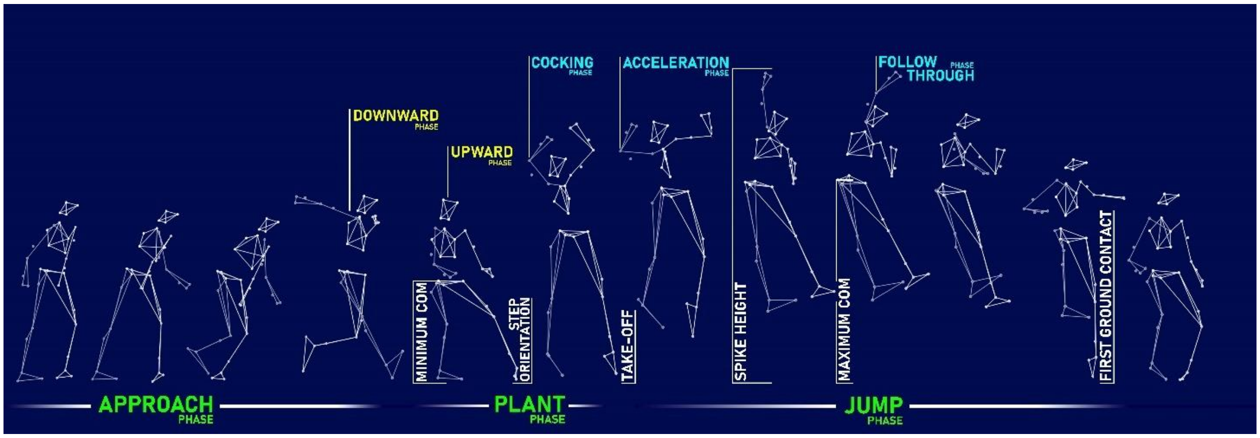

Figure 2. Phases of volleyball spike

The plant phase, where the athletes transform horizontal momentum to the vertical momentum, starts when the orientation leg (or step) places in front of the body (Fuchs, Menzel, et al., 2019). The main aim of this phase is to pre-activate the lower limb muscles (mentioned in previous paragraph) via SSC function (Carroll et al., 2019). The role of this part in a coordinated spike performance is vital as it synchronises the activiation timing of the muscles (Bobbert & van Ingen Schenau, 1988). In this phase, the whole body centre of mass (CoM) reaches to its lowest positions, while the torso-femur relative angles reaches to the minimum.

The final phase of the spike performance, where the attackers direct the ball towards opponents' court, is the jump phase. This phase starts by the time the attacker separates from the floor and finishes by the first ground contact (Fuchs, Menzel, et al., 2019). Nevertheless, as mentioned above, we focus on the spike performance till the impact (bill-htting) moment. Most of the movements, during the jump phase, are executed in the upper limbs, where the hitting arm experiences cocking, acceleration and follow-through phases (Wagner et al., 2014). Similar to the plant phase, where the athletes used the SSC function to activate the lower limb muscles for a better jump, the cocking phase activates the upper limb muscles (i.e., external oblique, pectoralis major, anterior deltoid, etc.) with the aim of increasing the hitting speed (Escamilla & Andrews, 2009; Reeser et al., 2010). The stored energy in upper limb muscles (in cocking phase) immediately used in the acceleration phase, in which the attackers try to hit the ball with the highest possible velocity (Fuchs, Menzel, et al., 2019). The follow-through phase starts after ball-impact moment and finishes when the arm velocities reach to its minimum (Escamilla & Andrews, 2009).

1.1.2 *Stretch-Shortening Cycle*

As covered above, the attackers constantly adopt the SSC function of lower and upper limb muscles in every spike performances. The SSC of muscle function stems from the fact that body segments are exposed to periodic impact or stretch stresses, in a movements such as walking or running (Fukutani & Herzog, 2021). Theoretically, the SSC is defined as an eccentric muscle contraction followed by an isometric transitional period, and immediately leading to an explosive concentric muscle contraction (Turner & Jeffreys, 2010).

Indeed, the eccentric contraction of the muscle stretches it, and stores elastic energy in the muscle fibers (Komi, 2003). The stored energy needs an actuator to release it, and explosively shorten the muscle length in the concentric phase (Nicol et al., 2006). In this regard, two organs act as an actuator in this eccentric-to-concentric transmition. First, the Golgi-tendon organ (GTO), which is a type of muscle-bound mechanoreceptor that contributes to proprioception, is found within the collagen fibers of tendons within the joint capsules (figure 3) (Oliver et al., 2021). Since the GTOs are located in series with the muscle fibers, any stretches of the tendons that is developed by all of the muscle fibers are sensed by GTOs (Oliver et al., 2021). After the GTOs sensed the stretches, the type Ib afferent fibers transmit these senses to the spinal cord. Thereafter, in an inverse myotatic reflex, the GTOs try to relax the muscle by returning it to the safe zone in an concentric contraction (Blum et al., 2021). These series of activites shorten the muscle length (in a concentric contraction) and aid in stored energy reuse for an efficient explosive contraction (Komi, 2003).

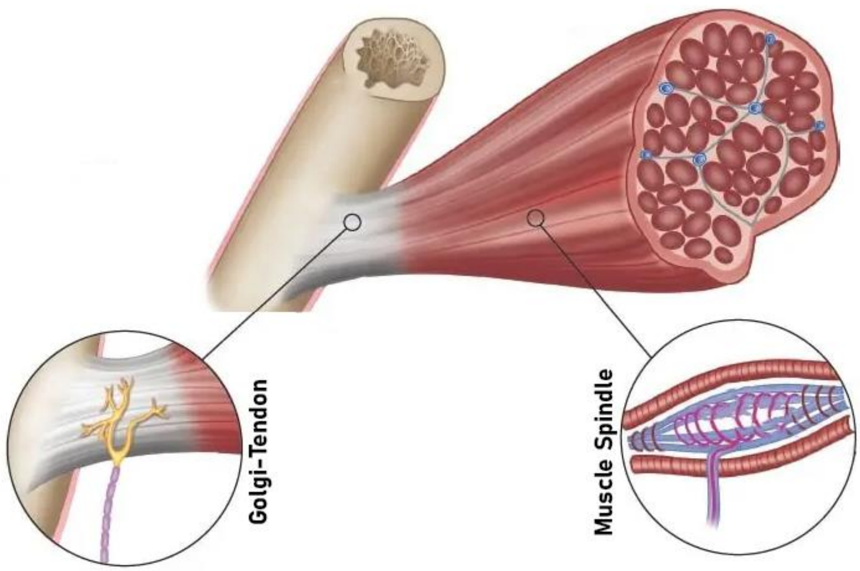

Figure 3. Golgi-tendon and muscle spindle, and their location in skeletal muscles.

Second organ is muscle spindle, which is described as the small, spindle-shaped sensory receptor in the middle of muscle fibers (Blumer, 2011). Muscle spindles run parallel to the muscle fibers, and are made up of numerous differentiated muscle fibers surrounded by a sindle-shaped connective tissue sac (Blumer, 2011). Similar to the GTOs, muscle spindles are sensitive the muscle stretching, either in phasic (rate of stretch) or in tonic (the length of stretch). When the muscle spindles get stimulated, they inhibit the muscle lengthenings by shortening the muscle length using myotatic reflex. This act, similar to GTOs, aids in an explosive muscle contraction, and results in a powerful contraction (Nicol et al., 2006).

Apart from its contributive impacts on concentric contraction of the muscles, the SSC helps in reduction of the metabolic cost in different actions (Bobbert & Casius, 2005). Further, involuntary nervous processes, enhanced coordination and increased active joint range of motion are other benefits of SSC function (Turner & Jeffreys, 2010). Due to which, usage of SSC function is an efficient approach in enhancement of jumping and hitting performance in volleyball spike. The SSC is popular with the Plyometric exercises among the coaches and trainers. A plethora of research studies investigated the SSC function (quality of the explosive strength) among volleyball players via analysis of Force-Time curve variables of vertical jump performance (Sarvestan et al., 2018; Slovák et al., 2021).

1.1.3 Force-time curve

The ability to jump high requires a synchronous timing of lower-and upper limb muscles activity in a coordinated manner. From kinetics point of view, the entire lower-and upper limb muscles (i.e., ankle plantar flexors, knee and hip extensors, and arm flexors) eccentrically stretch in the eccentric phase of jump (figure 4) (Laffaye et al., 2014). The eccentric phase starts by the descending locomotion of the CoM and finishes when the downward velocity of the CoM reaches to zero (Ebben et al., 2007). As discussed above, athletes try to reach the maximum possible stretching so that they use the stored energy in the concentric phase of the jump. The concentric phase starts when the upward vertical velocity of the CoM becomes positive and finishes when the athletes leave the ground (Ebben et al., 2007). Since volleyball spike jump adopts a countermovement pattern, previous studies investigated the countermovement jump as a tool to monitor athletic jump performance (Sarvestan et al., 2018; Sheppard et al., 2008).

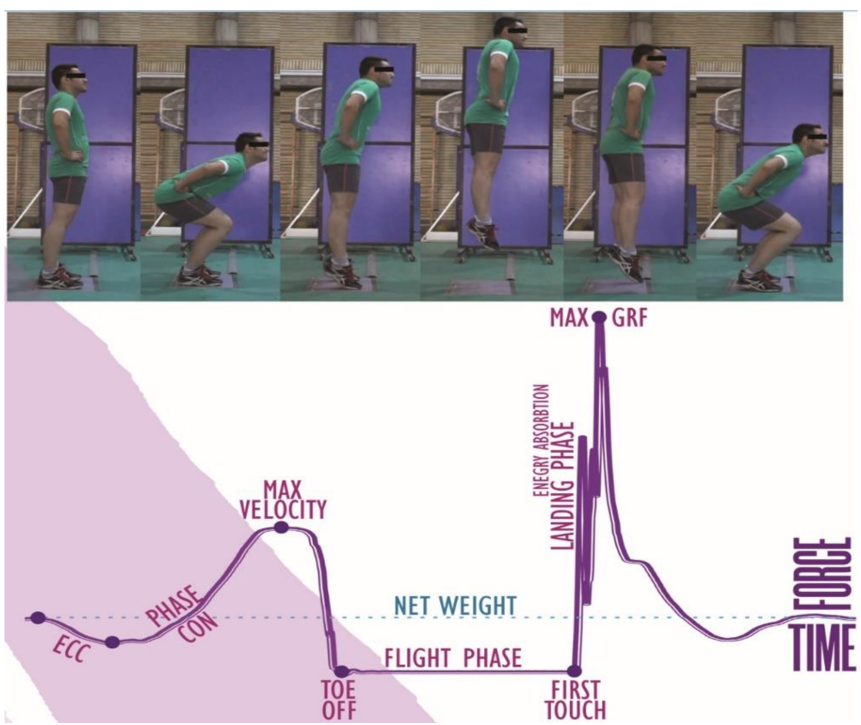

Figure 4. Force-Time curvature of countermovement jump.

Critical information about the athletic jump performance can be extracted from the force-time (F-T) curve variables of the countermovement jump (Laffaye et al., 2014). The time variables, force variables and the linked variables to these two parameters, such as impulse, power, reactive strength index, and rate of force development, have been studies in previous studies (Claudino et al., 2017; Laffaye et al., 2014; Slovák et al., 2021). This precise piece of information (which also could be observed from the shape of F-T curve) could highly help the coaches, trainers and scientists to understand the underlying mechanisms of the contributors (i.e., neuromuscular properties) to the jump performance among athletes.

Among the above-mentioned parameters, the Impulse was calculated as the area under the net F-T curve using the trapezoidal integration method (Sarvestan et al., 2018; Sole et al., 2018). Using the Newton's second law, the CoM acceleration was calculated (McMahon et al., 2017), and the instantaneous CoM velocity and displacement are calculated via first and second integration of acceleration data (McMahon et al., 2017). The power is also calculated as the multiplication of the force and velocity measures (Owen et al., 2014). The rate of force development is calculated as the first derivative of the F-T curve data (McLellan et al., 2011). The reactive strength index, which is globally known as the reactive jump capacity of athletes, is calculated by dividing the jump height by the time to take off (Suchomel et al., 2015).

1.1.4 Factors influencing volleyball spike performance

Through the literature, several physiological, anthropometrical, psychological, and biomechanical factors have been introduced as contributors to the volleyball spike performance (Melrose et al., 2007; H. Wagner et al., 2009). From physiological and anthropometrical point of view, age , height, lean body mass, shoulder|hip|thigh girth, strength and balance are the most influential elements in volleyball spike performance (Gladden & Colacino, 1978; Lidor & Ziv, 2010; Melrose et al., 2007).

Increment in age has been claimed to directly influence the serving and spiking speed among volleyball players (Melrose et al., 2007). Nevertheless, this could happen due to increment in lean body mass (muscles or bones girth) and strength of the athletes. According to the impulse-momentum relationship, an increment in the mass of the segment could, on the other hand, increase the applied force to the contacted body, and consequently, add up to its speed (Schilling et al., 2008). In a study conducted by Gladden and Colacino (1978), height was significantly correlated with the final standing of the national tournaments. Theoretically, athletes who are taller might have higher reaching points and a greater view of the opponents' court. On the contrary, with consistent claims on the importance of height, literature shows controversial results on the impacts of weight on the spike performance. For instance, it was claimed that elite players or national-level league players are heavier than sub-elite players (Spence et al., 1980), but other studies found no significant relationship between the weight and success in volleyball tournaments (Gladden & Colacino, 1978; Melrose et al., 2007).

In terms of strength, it has been highlighted that older volleyball players exhibit greater maximal isometric handgrip strength in comparison with their younger peers (Melrose et al., 2007). In fact, age had a positive significant correlation (r=0.7) with the strength measurers of volleyball players. As for the lower limbs strength, although older volleyball players depicted greater values, no significant correlation have been found between age and leg strength (Melrose et al., 2007). In another study, Slovák et al. (2021) found no increment in vertical produced force values as the age of volleyball players increases. To this effect, lack of relationship between the lower limb strength and volleyball jump heights represents that skill and coordination (how to employ the muscle forces, not how much of their forces) are the key elements in better jump performance (Melrose et al., 2007).

In terms of psychology, former experiences, game-related stress management and cognitive flexibility are introduced the main contributors to the volleyball spike performance (Melrose et al., 2007; Starkes & Allard, 1983). Previous studies portrayed that the players with longer background of volleyball training (here called experienced ones) could produce greater rates of force development, power and vertical velocities in comparison with the less experienced volleyball players in a real-game condition (Melrose et al., 2007; Slovák et al., 2021). In addition, it has been claimed that experienced volleyball players are able encode game information to a deeper level and portray superior recognition during the game (Starkes & Allard, 1983). Due to which, expert players are more able to handle the game-related stresses and cope with the managements. As for the cognitive flexibility, it was demonstrated that volleyball players have quicker reaction to the external signals during the competition (Starkes & Allard, 1983). Overall, from the psychological point of view, experienced volleyball players portray a better and highly stable performance during the game.

From biomechanical perspective, a set of kinetic and kinematic parameters are the main contributors to the volleyball spike performance success rate. As mentioned in the "*Force-Time Curve*" section, peak and average rate of force development, relative peak power and reactive strength index are the principal elements in the higher jump height among volleyball players (Sarvestan et al., 2018; Slovák et al., 2021). Among the kinematic variables, the approach phase speed, knee and hip joint angular velocities, and arm swing (vertical arm velocities) are addressed as the key parameters in higher jump heights in volleyball spike performance (Fuchs, Menzel, et al., 2019; Wagner et al., 2009). In the following section, the kinetics and kinematics contributing variables to the volleyball spike performance will be covered in details.

1.2 Overview of knowledge, and the questions leading to this research

Spikes are one of the most important contributors to the match success rate, as well as serves and blocks (Fuchs et al., 2021; Häyrinen et al., 2004). From a biomechanical point of view, spike jump heights are counted as the principal contributors to a successful spike performance (Fuchs, Fusco, et al., 2019; Fuchs, Menzel, et al., 2019). Reaching higher jump altitudes enables attackers with a better point of view over the opponents' playground and increases the availability of free spaces to hit the ball through (Fuchs et al., 2021). Thus, every attacker constantly tries to achieve the highest jump heights in order to increase the success rate.

Theoretically, attackers perform a 3- or 4-step approach followed by a quick countermovement in the plant phase to achieve the highest take-off velocities and jump as high as they can (Fuchs et al., 2021). This requires proper levels of lower limb muscles SSC recruitment to transfer horizontal velocities to vertical in an explosive action, and achieve the highest jump altitudes (Nicol et al., 2006). To this effect, a plethora of research studies tried to investigate the SSC capabilities of volleyball players using the countermovement

(CMJ) or spike jumps (SpJ) (Carroll et al., 2019; Sarvestan et al., 2018; Sheppard et al., 2008; Sheppard et al., 2009).

Among the studies, only two of them were conducted to analyse SpJ performance (Sheppard et al., 2008; Sheppard et al., 2009); nevertheless, they focused on the impacts of strength and conditioning training on force-time (F-T) curvature data. They brought up that increment in relative power (r=0.64) and force (r=0.46) values linearly increase the SpJ heights (Sheppard et al., 2009). Nonetheless, force and power were the sole F-T curve variables studied in their studies. In other studies conducted on the CMJ performance of young elite volleyball players, Sarvestan et al. (2018) found out that average (r=0.7) and relative peak power (r=0.75) have a significant relationship with higher jump heights. However, Carroll et al. (2019) questioned the relationship between the relative peak power and CMJ heights as they found relatively poor reliability (ICC=0.41) for relative peak power among volleyball players, while the CMJ heights reliability was quite strong (ICC=0.92).

The rate of force development (RFD) was another effective parameter in the achievement of higher jump altitudes (Cronin & Sleivert, 2005; McLellan et al., 2011). It has been shown that Peak RFD determines over 46% of vertical jump heights (McLellan et al., 2011), which represents individuals with greater RFD values exhibit higher jump heights. They represented that training methods emphasizing explosive technique that is designed to improve Peak RFD should lead to improvements in ultimate jump heights and consequently improve dynamic sports performance. In a study conducted by Earp et al. (2011), it was illustrated that higher eccentric loadings activate SSC function significantly more, aid in higher RFD values, and ultimately, increase jump altitudes. Due to this fact, they represented that CMJ results in significantly higher jump heights because of higher muscle fibre recruitments (which were activated in the eccentric phase of CMJ). Nevertheless, to our knowledge, no study was conducted to analyse F-T curve variables in sport-specific jump patterns. Furthermore, with all the above-mentioned facts in mind, the following questions arise:

- **What force-time curve variables are the main contributors to higher spike jump heights?**

In order to answer these questions, we conducted the first study entitled "*Force-time curve variables of countermovement jump as predictors of volleyball spike jump height*".

Abundant of research studies were conducted to analyze the kinematics of volleyball spike among attackers (Fuchs, Fusco, et al., 2019; Serrien et al., 2016a; H. Wagner et al., 2014; H. Wagner et al., 2009). Former studies tried to divide the spike performance into three phases including approach, plant and jump to precisely analyze it (H. Wagner et al., 2014; H. Wagner et al., 2009). They claimed that kinematics analysis of spike performance could reveal any deficits throughout the spike and aid in the improvement of training programmes (Serrien et al., 2016a).

As mentioned above, achieving higher jump altitudes is consistently highlighted as one of the most important parameters contributing to a better spike performance (Fuchs, Menzel, et al., 2019; Valadés et al., 2016). Besides, higher jump heights correspond to longer flight times, provides the attackers with relatively enough time to make the best decision for spiking (Ziv & Lidor, 2010). It has been generally believed that a harmonious movement patterning of lower and upper limbs (during approach and plant phases) is required to achieve higher jump altitudes (Fuchs, Fusco, et al., 2019).

Precisely speaking, attackers must transfer forward acceleration of COM to vertical acceleration in a harmonious flexion and extension movement of the ankle, knee, hip, shoulder and elbow joints (H. Wagner et al., 2009). It has been illustrated that this transfer linked with an increment of knee extension velocity $22°.s^{-1}$, would increase jump height by 1 cm in volleyball players (Fuchs, Fusco, et al., 2019). Furthermore, coordinated flexion of shoulder and elbow joints (arm swing) at the plant phase is highlighted to increase the jump heights from 10 to 28% (Chiu et al., 2014). This not only aids in increment of the vertical velocity of CoM at take-off but also places the upper limbs in a position to hit the ball effectively (Chiu et al., 2014). However, although a higher jump height could increase the chance of a successful spike performance, a coordinated movement of lower- to upper-limb segments can provide the attacker with the optimal condition for a successful spike performance. In other words, If a spiker has a high altitude during the spike but a poorly coordinated movement pattern, his or her success rate is likely to be lower than that of a spiker with a well-coordinated movement pattern, regardless of his or her jump heights.

Alongside the jump heights, spike velocity is another vital factor contributing to a successful spike performance (Fuchs, Menzel, et al., 2019; Valadés et al., 2016). In order to achieve an optimum spike velocity (for a successful spike performance), the pelvis, trunk, upper arm and forearm must coordinately transfer the angular momentum along the kinetic chain (Valadés et al., 2016; H. Wagner et al., 2014). In lay terms, the velocity of proximal segments accumulatively transferred to the distal segments, and consequently, the ball with have the maximum velocity. To this end, the following question arises:

- ❖ **What variables are the main contributors to the volleyball spike success rate?**

To find the answer to this question, we conducted the study entitled "*Kinematic differences between successful and faulty spikes in young volleyball players*".

As previously mentioned, highly coordinated neuromuscular activities are needed for a successful spike performance (Serrien et al., 2016b). Various physical attributes (i.e., muscle strength, movement timing or coordination) underpin effective movement coordination in spike performance (Oliveira et al., 2020; Serrien et al., 2016b). Although the role of movement coordination in the successful accomplishment of sports activities is highlighted, the notion of movement coordination analysis is recently developed by researchers (Needham et al., 2016; Robertson et al., 2013).

Among the techniques developed for the quantification of movement coordination, the discrete relative phase (DRP) was one of the first methods used in block performance of volleyball players (Hughes & Watkins, 2008). As its name portrays, the DRP method is generally used in discrete sports movements. This method provides the researchers only with a number regarding the peak movement of two independent joints or segments in a particular activity (Robertson et al., 2013). To this end, this method was not popular enough among researchers and has not been recently used as it could not address the full complexity of the original signals (Robertson et al., 2013).

Continuous relative phase (CRP) was another method adopted to calculate the movement coordination in cyclic human activities (Huang et al., 2020; Miller et al., 2010). This method is globally considered a higher-order measure of the coordination among two joints or segments in a system (Robertson et al., 2013). The dynamics of bimanual coordination have been studied using CRP analysis to discover stability and transitions (Kelso, 1995). Given that this method analyses the time-series data over time, it could provide the researchers or researchers with better insights into the coordination pattern throughout the movement. Nevertheless, given that the volleyball spike is a discrete action, the CRP is not a suitable tool to analyse its coordination patterning.

Vector coding (VC), which is another method of quantifying movement coordination, has become more popular among researchers for the analysis of movement coordination and coordination variability (Needham et al., 2014; Robertson et al., 2013). This method is more flexible in comparison with DRP and CRP, as it could be used in both discrete and continuous movements. To this effect, VC has been abundantly used in sports- and clinical-related studies (Needham et al., 2014; Sarvestan et al., 2020). Nevertheless, given that this method only measures the coordination patterning between two joints or segments, it cannot provide information regarding the whole-system coordination patterning in a particular task. Analysis of several couplings (i.e., ankle-knee to wrist-elbow) in three dimensions would be an overwhelming analyzed data that might not suit the volleyball players or coaches. To this effect, there must be a simple language to communicate with coaches or players about improving their performance.

The notion of the self-organising-map (SOM) has been recently employed to investigate the human movement in a disparate dimension (Serrien et al., 2017). SOM is a class of artificial neural networks (unsupervised machine learning) that could identify complex patterns in multidimensional sports activities (Kohonen, 2001; Serrien et al., 2016b). SOMs can reduce a multi-dimensional kinematic time series expressing whole-body coordination to a two-dimensional (2D) coordinate trajectory using a two-dimensional (2D) grid (Serrien et al., 2016b). This mapping is done in such a way that the dataset's original topology is retained to the greatest extent possible, (e.g., patterns that are similar in the higher-dimensional kinematic space are mapped near together in the 2D SOM space). As an example, SOMs could illustrate and predict the coordination profile in golf putting with increment in target distance (Lamb et al., 2011). More recently, Serrien et al. (2016b) investigated the whole body coordination patterning of volleyball spike among sub-elite and elite males and females volleyball players using SOMs. Given that volleyball spike movement patterning consists of a set of non-linear variables, employing a multivariate analysis (i.e., SOM) could be a proper approach for the analysis of whole-body coordination patterning of the players.

To that end, we conducted the study entitled "*Analysis of Whole-Body Coordination Patterning in Successful and Faulty Spikes Using Self-Organising Map-Based Cluster Analysis: A Secondary Analysis.*" to answer the following question:

- **Is that lower limb or upper limb that play a pivotal role in spike success rate?**

Nonetheless, the notion of individuality in sports-related tasks highlights the fact that generalizability of the outcomes for the entire players might result in a poor diagnosis of individual performance deficits. The motor control system constantly adopts new controlling strategies to maintain the whole-structure coordination patterning in a particular task (Shafizadeh et al., 2019). This magnificently coordinates the environment and the central nervous system (CNS) to regulate the movement patterning and accomplish the desired task. Although this coordination orders the neuromusculator to adapt various degrees of freedoms (DOF) to deal with perturbations, lack of sufficient knowledge on the role of internal variables (how the patterning is ordered to be performed by CNS) in complicated sports tasks exists.

According to the concept of dynamic system theory, each motor performance (neuromusculator system) is uniquely self-organized in response to the existing constraints (Stergiou & Decker, 2011). Since the volleyball spike is a sophisticated task, it requires high levels of cognitive capacities to be performed effectively, particularly under different game-related constraints (game-related stresses, blocks, etc.). As the working memory (short term memory) has a limited capacity to recall and run the entire spike performance, it is predicted that most of the spike patterning is automatically ran in lower levels of the brain (Latash et al., 2002; Runswick et al., 2018). To this effect, we conducted the study entitled "Whole-body coordination patterning in volleyball spikes under various task constraints: exploratory cluster analysis based on self-organising maps" to investigate if we can generalize the outcomes of the 3rd study as a training program for volleyball players. In fact, the question for conducting the fourth study was:

- ❖ **Can we generalize the spike performance accomplishment/errors to all players?**

1.3 Aims

1.3.1 General aim

This study was aimed to investigate the biomechanical factors contributing to the volleyball spikes success rates among elite young volleyball players

1.3.2 Specific aims

Study 1: Analyzing the force-time curve (kinetics) variables that contribute to higher spike jump heights among young elite volleyball attackers.

Study 2: Analyzing the kinematics factors contributing to successful and faulty spikes among young elite volleyball attackers.

Study 3: Investigating the whole-body coordination patterning (whole-body joints angles and angular velocities) differences between successful and faulty spikes among young elite volleyball attackers.

Study 4: Analyse the uniqueness of volleyball spike coordination patterning under different task constraints among young elite volleyball attackers.

1.4 Research questions

1- What force-time curve variables are the main contributors to higher spike jump heights?

2- What variables are the main contributors to the volleyball spike success rate?

3- Is that lower limb or upper limb that play a pivotal role in spike success rate?

4- Can we generalize the spike performance accomplishment/errors to all players?

1.5 Hypotheses

a. Relative power, RFD and impulse values are significantly correlated with higher SpJ heights.

b. Take-off velocity, jump heights, spike height and spike velocity values are significantly greater in successful spikes in comparison with faulty spikes.

c. Whole-body coordination patterning will be significantly different between successful and faulty spikes.

d. Individuals have their own unique coordination patterning in volleyball spike performance.

2 Published Manuscripts

In the following pages, four published manuscripts will be presented. These four scientific papers are conducted with the purpose of addressing the research questions and hypotheses. These four research studies are:

1- Sarvestan, J., Svoboda, Z., & de Oliveira Claudino, J. G. (2020). Force-time curve variables of countermovement jump as predictors of volleyball spike jump height. *German Journal of Exercise and Sport Research*, *50*(4), 470-476.

2- Sarvestan, J., Svoboda, Z., & Linduška, P. (2020). Kinematic differences between successful and faulty spikes in young volleyball players. *Journal of Sports Sciences*, *38*(20), 2314-2320.

3- Sarvestan, J., Svoboda, Z., Alaei, F., & Mulloy, F. (2021). Analysis of Whole-Body Coordination Patterning in Successful and Faulty Spikes Using Self-Organising Map-Based Cluster Analysis: A Secondary Analysis. *Sensors, 21*(4), 1345.

4- Sarvestan, J., Svoboda, Z., Baeyens, J.-P., & Serrien, B. (2020). Whole-body coordination patterning in volleyball spikes under various task constraints: exploratory cluster analysis based on self-organising maps. *Sports Biomechanics*, 1-15.

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Force-time curve variables of countermovement jump as predictors of volleyball spike jump height

Introduction

Volleyball spike performance, as one of the principal scoring elements in volleyball competitions, is directly influenced by vertical jump height (Mosier, Fry, & Lane, 2019; Sarvestan, Cheraghi, Sebyani, Shirzad, & Svoboda, 2018; Sole, Mizuguchi, Sato, Moir, & Stone, 2018). Fundamental to achieving the highest possible jump height is the capability to adopt and recruit a harmonious muscular activation of both lower and upper extremities (Serrien, Ooijen, Goossens, & Baeyens, 2016), which highlights the significance of an efficient neuromuscular system (Claudino et al., 2017). A wealth of studies have been designed to conduct in-depth investigations on athletic jump performance using various jumping strategies, including countermovement jump (CMJ) and squat jump (SJ) (Claudino et al., 2017; Laffaye, Wagner, & Tombleson, 2014; Markovic, 2007; McMahon, Murphy, Rej, & Comfort, 2017; Mosier et al., 2019; Sarvestan, Cheraghi, Shirzad, & Svoboda, 2019a; Sole et al., 2018). Given the similarity between the nature of CMJ and most sports-related jumps, such as in basketball and volleyball—in which the athletes activate muscle fibres using a stretch-shortening cycle (SSC; Komi, 2003)—they were mainly done to monitor the efficiency of training programs and the neuromuscular status of athletes for identification of supercompensation, fatigue, or weaknesses, or to detect the return-to-play time after rehabilitation (Claudino et al., 2017; Gathercole, Sporer, Stellingwerff, & Sleivert, 2015; Laffaye et al., 2014; Markovic, 2007; McMahon et al., 2017; O'Malley et al., 2018; Sarvestan et al., 2018; Sole et al., 2018).

At present, a variety of extracted derivatives from the force-time (F-T) curve, including force, power, velocity, impulse, and modified reactive strength (RSImod), have been precisely analysed during unweighted eccentric and concentric phases of CMJ performance in order to find the best contributor to jump height performance (Ebben & Petushek, 2010; Kirby, McBride, Haines, & Dayne, 2011; Laffaye et al., 2014; Marques et al., 2015; McMahon et al., 2017; Sarvestan et al., 2018; Sarvestan et al., 2019a). It has been previously found that force measures, whether absolute or relative, have no significant relationship to ultimate jump height among athletes (Claudino et al., 2017; Sarvestan et al., 2018), which might be due to several reasons, including muscular activity patterns, musculoskeletal redundancy, or movement timing. Nevertheless, force-related variables, such as rate of force development (RFD), explosive strength, power, velocity, and acceleration, have been demonstrated to make meaningful contributions to jump height (Marques et al., 2015; Sarvestan et al., 2019a). The concentric RFD, which is defined as the capability of muscle fibres to rapidly develop force measures, has been verified to have large degrees of association with jump height ($r = 0.68–0.82$; Marques et al., 2015; McLellan, Lovell, & Gass, 2011). Nevertheless, a variety of inconsistent results regarding the relationships between RFD values and jump heights seems to be problematic in the tracking of neuromuscular status to assess athletic jump performance (Claudino et al., 2017).

On the other hand, increments in peak power measures, which are linearly related to force and velocity measures, also greatly aid in higher jump heights because larger numbers of muscle fibres contract in a relatively short time (Alemdaroğlu, 2012; Rice et al., 2017). Athletes who participate in sports that require jumping have recorded significantly greater values of produced power during squat jumps (McBride, Kirby, Haines, & Skinner, 2010). Furthermore, it has been suggested that peak power measures are the sole predictor of vertical jump height (Dowling & Vamos, 1993; McBride et al., 2010). Nonetheless, there is still controversy about the impact of power measures on jump height given the poor reported relationship between peak power mea-

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sures and ultimate jump height (Sarvestan et al., 2018).

The modified reactive strength index (RSImod), which is globally known as the ability to execute an SSC performance in a relatively quick action, has been confirmed as a reliable parameter to monitor athletic jump performance and diagnose the probability of anterior cruciate ligament injury (Ebben & Petushek, 2010; Flanagan, Ebben, & Jensen, 2008). Previous research investigations adopted the RSImod to assess the athletic jump performance in different athletic teams, including those for volleyball, soccer, tennis, and baseball (Robbins, 2011; Suchomel, Sole, Bailey, Grazer, & Beckham, 2015). Although the RSImod is generally employed as a diagnostic tool in rehabilitation sciences, its application to other types of jumping that include SSC would enable trainers to assess the maximal force development capability or explosive power (Ebben & Petushek, 2010; Flanagan et al., 2008) or to monitor the neuromuscular status of athletes (McMahon, Suchomel, Lake, & Comfort, 2018). Although it has been previously verified that RSImod is one of the most valuable F-T curve parameters for assessing athletic jump performance or identifying return-to-play of injured athletes (Flanagan et al., 2008; Suchomel et al., 2015), it is not clear to what extent this variable could play a role in jump performance under game-like circumstances.

In addition, the net impulse (or the area under the F-T curve) is also one of the most reliable parameters for the prediction of athletic jumping performance (Hamill & Knutzen, 2006; McBride et al., 2010). It has been mentioned that different jumping strategies result in different net impulse measures due to different F-T curve characteristics (McBride et al., 2010). Trainers and coaches were formerly advised to use net impulse in order to analyse individual jump performance alterations (McBride et al., 2010). Nevertheless, no investigation to date has been conducted to observe to what extent the F-T curve variables of CMJ can predict athletic jump performance in a game-like situation. This information could provide trainers and coaches with a practical analytical tool to track athletes' sports-specific jump performance and can be further used as a gold standard in different sports fields.

Based on the literature discussed above, although many research studies have investigated CMJ to observe relationships between F-T curve variables and CMJ heights, there is a lack of information regarding the contributions of F-T curve variables (derived from CMJ) to spike jump performance during game conditions. This information could aid in predicting athletic jump performance in a game-related situation, especially for coaches or trainers who are limited in their tools for assessing their athletes' performance. To this end, this study was designed to investigate the contribution of the F-T curve variables of CMJ to verify what determines the spike jump height (SpJH, in which the attackers jump to spike during a game-like condition) in young elite volleyball attackers during a simulated game-like condition. It was hypothesised that power, concentric net impulse, RFD, and reactive strength index values that are derived from CMJ F-T curve variables would have a large contribution to SpJH among young elite volleyball players.

Methods

Participants

A total of 13 young elite male volleyball players (age: 15.4 ± 0.7 years, height: 190.4 ± 5.8 cm, weight: 76.2 ± 5.7 kg, experience: 6.5 ± 0.7 years) voluntarily participated in this study. The participants had experience participating in international competitions and were in national training sessions for Under-17 international competition while the measurement procedure was taking place. No acute musculoskeletal injuries, such as muscle, ligament, or tendon torsion, joint dislocation, or bone fracture, were reported by the players within the previous 12 months or during the experiment. The written informed consent was explicitly described to the participants and their parents and was signed by them prior to data sampling. The procedures were in compliance with the 1964 Helsinki Declaration and its later amendments.

Procedure

After a 10-min dynamic cardiovascular warmup followed by a 10-min volleyball-specific warmup, the players were instructed to perform three CMJs using arm swings (interspersed by 3-min rest intervals to prevent fatigue) to a self-selected knee flexion (McMahon et al., 2017; Sarvestan et al., 2018) on a 37 cm × 37 cm force platform (Pasport PS-2142, 1000 Hz; Pasco, Roseville, CA, USA,). Previous studies adopted different strategies to perform the CMJ, such as akimbo style or with arm swing (Mosier et al., 2019; Sarvestan et al., 2018); nevertheless, in this study we adopted the CMJ with arm swing in order to simulate spike jump performance, in which players take advantage of arm-swing velocity to obtain higher jump heights. The vertical F-T data set was exported and analysed using Microsoft Excel (2016 version; Microsoft, Redmond, WA, USA).

After the CMJ performance, the participants prepared for spike jump performance. To this effect, 39 passive reflective 14-mm–diameter markers were attached to the bony landmarks employing the plug-in gait model by an experienced researcher using a Vicon motion analysis system (Oxford Metrics, Oxford, UK). Thereafter, the players performed six spikes with the presence of two defences in a game-like simulated condition. Although previous studies tried to keep the ball position in a constant place (Wagner, Tilp, Von Duvillard, & Müller, 2009), performance reliability while applying this technique seems to be lower than that obtained under game-like conditions (Serrien et al., 2016). Hence, an expert setter was instructed to set the ball with the highest possible accuracy. Using six optoelectronic cameras (Vicon Motion Systems, Oxford Metrics, Oxford, UK), the spatiotemporal trajectory of detected markers was recorded at the sampling rate of 200 fps. Employing Vicon Nexus software (version 1.8.6, Oxford Metrics, Oxford, UK), the data reconstruction, labelling, and gap-filling process (pattern and spline methods) were conducted. Applying the fourth-order Butterworth filter (zero lag; 10 Hz cut-off frequency), the data-smoothing procedure was also carried out.

Data analysis

In this study, we divided CMJ performance into two eccentric and concentric phases (Sarvestan et al., 2018). The eccentric phase started when the centre of mass (CoM) vertical velocities decreased to the lowest values (negative values) and ended when the velocity measures again increased from negative values to zero (Sarvestan et al., 2018). The concentric phase started immediately after the eccentric phase and lasted until the take-off moment (when the vertical applied force was equal to zero; Sarvestan et al., 2018). Employing the trapezoidal integration of the F-T curve from the start of unweighting to the take-off phases, the area under the net F-T curve (with the body weight excluded) was calculated as impulse measures (Sarvestan et al., 2018; Sole et al., 2018). The CoM acceleration was calculated using Newton's second law of motion (McMahon et al., 2017). Adopting the first and second integration of acceleration measures, instantaneous velocity and displacement of CoM were also calculated (Sarvestan et al., 2018).

Furthermore, the power measures were calculated by multiplying the force and velocity measures at each time point (Owen, Watkins, Kilduff, Bevan, & Bennett, 2014). Vertical CMJ height was also calculated using the impulse–momentum relationship (Sánchez-Sixto, Harrison, & Floría, 2018). In order to normalize the entire recorded data, the maximum measures of vertical force and power were divided by the body mass. For calculation of RSImod, the jump height (m) was divided by time to take-off(s) (Barker, Harry, & Mercer, 2018; Ebben & Petushek, 2010; Suchomel et al., 2015). For calculation of average RFD, the maximum produced concentric force was divided by the time taken to reach maximum peak force, and the peak RFD was obtained from the exhibited maximum force value throughout the first derivative of the F-T curve (McLellan et al., 2011). The average of three trials was processed for further statistical analysis.

Regarding the SpJH, the total body CoM was computed by applying a regression formulation on the segment positions (Dempster, 1955), and the SpJH was calculated by subtracting the maximum CoM height from the standing position CoM in a vertical direction. The average of six SpJHs was further used in statistical analysis.

Statistical analysis

Normality of data distribution was tested and approved using the Shapiro–Wilk statistical test. Using the interclass correlation coefficient (ICC) statistical test, the reliability of measured data among all trials was assessed. The ICC assessed within-session reliability to recognize the error scores (Weir, 2005). The ICC values were interpreted as follows: <0.4 poor; 0.4–0.7 fair; 0.7–0.9 good; and >0.9 excellent. Pearson's product correlation test was employed to analyse the association between F-T curve variables and both CMJ and SpJH. According to the modified correlation scale, the magnitudes of the correlations were defined as follows: $r < 0.1$ trivial; 0.1–0.3 small; >0.3–>0.5 moderate; >0.5–0.7 large; >0.7–0.9 very large; >0.9 nearly perfect; and 1 perfect (Hopkins, Marshall, Batterham, & Hanin, 2009). For further regression analysis, the variables that showed a significant correlation with jump heights were included, and the coefficient of determination (R^2) was adopted for the interpretation of relationships between the variables (Thomas, Nelson, & Silverman, 2015), at a significance level of $\alpha = 0.05$. To justify the family-wise error for the statistical significance, the Holm–Bonferroni corrections were conducted. The Statistical Package for the Social Sciences (version 23; IBM, Armonk, NY, USA) and Microsoft Excel (2016 version; Microsoft, Redmond, WA, USA) were employed to conduct the entire statistical analysis.

Results

A high within-trial reliability between three trials of CMJ heights (ICC = 0.92, standard error of measurement [SEM] = 1.86%) and six trials of spike jump (minimum ICC = 0.86, SEM = 1.73%) was illustrated. As expected, the average of six SpJHs (78.39 ± 4.65) was more than the average of three CMJ heights (50.46 ± 6.58). A significant correlation was demonstrated between average CMJ heights and SpJHs ($r = 0.68$, $r^2 = 46\%$). Descriptive measures of F-T curve variables of CMJ performance, their standard errors of measurement, and correlations with SpJH are represented in Table 1. Significant correlation was illustrated

Abstract

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Force-time curve variables of countermovement jump as predictors of volleyball spike jump height

Abstract
Force-time (F-T) characteristics of countermovement jump (CMJ) are globally referenced as the main descriptors of athletic jump performance, particularly for volleyball players. Nevertheless, it is still unclear to what extent the vertical jump performance during testing is associated with jump performance during game-like conditions. This study was designed to investigate the association between F-T curve variables derived from CMJ, including movement timings, force, velocity, power, rate of force development (RFD), modified reactive strength index (RSImod), and net impulse with spike jump height during game-like circumstances. Thirteen young elite volleyball players performed three CMJs and six spike jumps in game-like circumstances. Pearson's product correlation test portrayed a significant correlation between spike jump height and peak RFD ($r = 0.75$), average RFD ($r = 0.76$), RSImod ($r = 0.56$), and concentric net impulse ($r = 0.61$). Multiple regression analysis also showed that these factors have a strong contribution for predicting spike jump heights (71%). The findings of this study emphasise the importance of RFD, concentric net impulse, and RSImod values in the precise analysis and prediction of volleyball attackers' spike jump height during game-like conditions.

Keywords
Net impulse · Reactive strength index · Rate of force development · Stretch-shortening cycle

Table 1 Descriptive measures of F-T curve variables (from CMJ) and their correlation with CMJ height and spike jump height

Variables		Mean ± SD	SEM (%)	Spike jump height	
				r	p
Power (w)	Take-off velocity (m.s^{-1})	3.43 ± 0.56	0.184 (5%)	0.26	0.202
	Peak power	5684 ± 1340	254 (4%)	0.23	0.219
	Average peak power	5401 ± 1279	269 (5%)	0.19	0.264
	Relative peak power	69.30 ± 15.34	4.45 (6%)	0.27	0.193
Force (*N*)	Peak force	1959 ± 226	52 (3%)	0.11	0.357
	Average peak force	1878 ± 215	54 (3%)	0.05	0.431
	Relative peak force	24.14 ± 2.21	0.796 (3%)	0.22	0.244
RFD (*N*.s^{-1})	Peak RFD	10104 ± 1249	362 (4%)	0.75[b]	0.000
	Average RFD	5677 ± 433	98 (2%)	0.76[b]	0.000
RSImod	–	0.251 ± 0.031	0.022 (3%)	0.56[a]	0.042
Net Impulse (*N*.kg^{-1})	Eccentric net impulse	1.12 ± 0.17	0.044 (4%)	0.18	0.274
	Concentric net impulse	3.18 ± 0.43	0.118 (5%)	0.61[a]	0.013

[a]Represents significance at $\alpha < 0.05$
[b]Represents significance at $\alpha < 0.01$
CMJ countermovement jump; ***SD*** standard deviation; ***SEM*** standard error of measurement, presented in absolute and relative results; ***RFD*** rate of force development; ***RSImod*** modified reactive strength index

Table 2 Multiple regression analysis between peak RFD, average RFD, RSImod, and concentric net impulse with spike jump height

Independent variables	Spike jump height				
–	Standardized β coefficient	β significance	R2	Adjusted R2	Model significance
Model 1	–	–	0.713	0.685	<0.001
Peak RFD	0.638	0.005	–	–	–
Average RFD	0.651	0.003	–	–	–
RSImod	0.422	0.037	–	–	–
Concentric net impulse	0.495	0.012	–	–	–

RFD rate of force development, ***RSImod*** modified reactive strength index, ***R2*** coefficient of determination

between peak RFD ($r = 0.75$, $r^2 = 56\%$), average RFD ($r = 0.76$, $r^2 = 58\%$), RSImod ($r = 0.56$, $r^2 = 31\%$), and concentric net impulse ($r = 0.61$, $r^2 = 37\%$) with SpJH. Nevertheless, no significant relationship was depicted between movement timing, velocity, force, or power measures with jump heights. Furthermore, as **Table 2** illustrates, the results of regression analysis showed that peak RFD, average RFD, RSImod, and concentric net impulse had the most contribution in predicting jump height, with 71% of the prediction rate.

Discussion

This study aimed to investigate which F-T curve variables have the most contribution in indicating SpJH in game-like circumstances among young elite volleyball players. The main findings of this experiment show that the RFD, concentric net impulse, and RSImod had significant correlation with SpJH, while no significant correlation was observed between velocity, force, or power measures with SpJH. The regression analysis also portrayed that a model summary of all mentioned variables (peak and average RFD, concentric net impulse, and RSImod) had a significantly high contribution in anticipating SpJH (71%).

Prior to interpretation of the outcomes of this study in the upcoming paragraphs, it should be taken into consideration that although the correlation between the CMJ heights and SpJHs was significant, the prediction rate of 46% may not be strong enough to claim with certainty that the mentioned F-T curve variables can precisely predict the SpJH. Nevertheless, the findings of this study would be useful for volleyball trainers and coaches who desire to monitor their athletes' spike jump performance using CMJs.

The CMJ height, as the most visible indicator of lower-limb muscular strength, was illustrated to reveal 46% of SpJH, with a positive correlation of $r = 0.68$. Initially, and due to the fact that CMJ height was formerly employed to monitor the lower-limb explosive-strength capability of athletes, it was expected that the association between CMJ height and SpJH would be higher (Sarvestan et al., 2018; Sarvestan, Cheraghi, et al., 2019). Nevertheless, given the different strategies adopted by attackers for a spike jump, such as triple-step running in the approach phase, which increases the CoM horizontal velocity and aids in the take-off phase, or trunk and head angles to follow the ball trajectory, it could be concluded that other parameters, including segmental coordination or game-related situations, might have a greater role in SpJH, and attackers do not employ the maximal explosive strength of the lower-limb muscles in spike performance during a game (Sarvestan et al., 2018; Wagner et al., 2009). Furthermore, given such varied strategies adopted for use during a spike jump, the pattern of recoiling the elastic energy might undergo different circumstances (Fukashiro, Komi, Järvinen, & Miyashita, 1995; Wagner et al., 2009). Hence, it is strongly advised to investigate the impacts of different jumping strategies, particularly in the upper limbs, to analyse jump performance in conditions similar to sport-specific jumping performance.

Interestingly, the results showed that the peak and average RFD values had, respectively, a 56% and 58% contribution to SpJHs, which were the strongest predictors among all the F-T curve variables. These outcomes indicate that the capability of the lower-limb muscles to develop the produced force could play a vital role in jump height during game-like conditions. These findings support the outcomes of a study conducted by McLellan et al. (2011), who reported a strong positive relationship between RFD and vertical jump height. Such a meaningful contribution to the prediction of SpJH demonstrates that attackers efficiently activate and govern the coupling between the neural and muscular systems to execute a highly coordinated, rapid contraction and to jump higher (Maffiuletti et al., 2016; Wagner et al., 2009). Simply explained, in the approaching phase of spike performance, attackers increase the CoM horizontal velocity in triple-step running and then transfer it to CoM vertical velocity in the planting phase using the SSC function of the ankle, knee, and hip joint extensors (Wagner et al., 2009). Achieving such coordinated, harmonious activation of muscles in a relatively short period of time demands a highly powerful neuromuscular status, which RFD could reliably exhibit in athletic jumping performance. From a practical point of view, and as illustrated by the outcomes, it is not the amount of applied force that aids in jump height but rather the pattern of applying the force that paves the way for a higher jump height, which is governed by an excellent coupling between the neural and muscular systems. To this effect, it is highly suggested to enhance the sports-specific jumping strategy, along with strengthening the muscles, in order to efficiently recruit the best muscle function during jump performance. Nevertheless, because the stepping phase of a spike jump is different from that of a CMJ—basically, the orientation step is in front—it is still not clear which leg has the most contribution in higher SpJHs (H. Wagner, M. Tilp, S. Von Duvillard, & E. Müller, 2009).

Several studies reported an almost weak relationship between RFD and CMJ height using arm swings (Lees, Vanrenterghem, & De Clercq, 2004; Vanezis & Lees, 2005). The main reason for such a discrepancy in outcomes seems to be the manner of obtaining the RFD measures, as other researchers employed isometric muscle contraction (Vanezis & Lees, 2005). In this study, we tried to obtain the RFD measures during the natural performance of the muscle in CMJ using a force platform, which might be the main source of difference. The logic behind employing the CMJ using arm swing was the similarity in nature of this jump with the spike jump, in which athletes bend their knees and trunk and use their arm swing to efficiently recruit the SSC and, consequently, jump higher (Komi, 2003; Sarvestan et al., 2018; Sarvestan, Riedel, Gonosová, Linduška, & Přidalová, 2019b). Although several studies have investigated the isolated lower-limb muscle status using akimbo-style CMJ (Sarvestan et al., 2018; Sarvestan et al., 2019a), this upper limb positioning is recommended to monitor the neuromuscular status and determine the best possible performance (Claudino et al., 2017; Claudino et al., 2016; Claudino et al., 2012). On the other hand, using arm swings seemed to increase the data reliability as it keeps the movement coordinated by using the hands in a harmonious way, mainly when the assessment seeks to achieve a performance more similar to the spike movement (i.e., during a game situation).

With a 31.4% contribution in the prediction of SpJH, the RSImod variable was demonstrated to be the other important predictor of jumping performance among volleyball attackers. These results were in line with previous studies, which included nonathlete males and females and two groups of elite and collegiate basketball players, in which the investigators reported that the capability to develop the produced force (explosive strength) plays a significant role in ultimate jump height (Ebben & Petushek, 2010; Sarvestan et al., 2019a). As discussed above, several other parameters, such as three-step running before the jump or neck and head positions, might contribute to spike jump performance. Therefore, it could be claimed that the motor coordination underwent diverse degrees of freedom, the SSC was activated in various manners, and consequently the RSImod contribution to SpJH was lessened due to the different adopted strategies. On the other hand, the RSImod values reported in this study were higher than those found in previous studies (Flanagan et al., 2008; Sarvestan et al., 2018; Suchomel et al., 2015), which might be due to different methods of jumping performance, as the attackers used arm swing.

One of the exceptional outcomes of the current study was the high prediction rate of concentric net impulse in SpJH (37.2%). This notion is supported by the studies previously conducted on jump performance among sport sciences students, which reported a relatively high correlation between net impulse and jump height (Kirby et al., 2011; Mizuguchi, Sands, Wassinger, Lamont, & Stone, 2015). In contrast to the outcomes of this study, previous studies found that neither eccentric nor concentric impulse had a significant correlation with CMJ height among volleyball players (Dowling & Vamos, 1993; Sarvestan et al., 2018). Such contradictory outcomes may be due to different methods of calculating jump height. In this study, we adopted the impulse–momentum relationship for calculation of jump height, whereas previous studies employed take-off velocity measures for calculating ultimate jump height, which have been mentioned as having visible differences (Sarvestan et al., 2018; Sarvestan et al., 2019a). Second, the entire positive portion of the F-T curve was previously utilized for calculation of impulse, while some part of this positive area (until the CoM velocity moves to positive values, or the start of the concentric phase) still belongs to the countermovement stretching phase (Dowling & Vamos, 1993). To this effect, this study used an identical approach adopted by Mizuguchi et al. (2015) in order to precisely calculate the net impulse in the concentric phase of CMJ. Furthermore, the significant correlation between concentric net impulse and SpJH reveals that the area under the concentric portion of the F-T curve could be considered an indicator of jump height status of volleyball spike jump performance. Nevertheless, it is highly recommended to accurately analyse this portion of the F-T curve variable in the event that individual athletes might portray different F-T curves while achieving the same jump heights (Mizuguchi et al., 2015).

On the other hand, the results of this study portrayed no significant correlation between take-off velocity measures and SpJHs. From a physics point of view, and based on the impulse–momentum relationship, velocity is the main dependent variable that contributes to jump height (Halliday, Resnick, & Walker, 2013). Nevertheless, because this study adopted concentric phase net impulse for calculation of jump height, this difference could be rational. Additionally, in this study we investigated the correlations between the take-off velocities of CMJ with SpJHs. Therefore, since the spike jump strategies (in which the attackers utilize more horizontal velocities) are different from the CMJ strategies, we may claim that the lack of relationships between these two parameters could be logical.

Limitations

Given the difficulty of planting the force platforms inside the playing-ground floor, we were not able to measure the F-T curve variables during a game-like spike jump; therefore, we used kinematic data for the calculation of jump height as an indicator of spike jump performance, using one of the methods considered gold standard for the kinematic measures. To this effect, comparing CMJ performance with spike jump performance during a game-like condition using a force platform is proposed for further investigations in this area. Furthermore, due to this study's small sample size ($n = 13$), which is one of the most important elements in statistical power, the results must be interpreted with caution.

Conclusion

The outcomes of this study mainly imply that the RFD values, either peak or average, and RSImod may be employed in the assessment of attackers' explosive strength patterns in volleyball spike jump performance. Because the RFD is strongly influenced by the central nervous system, any alterations in athletes' movement coordination could highly deteriorate the muscle functions, applied force, and, consequently, ultimate jump heights. Therefore, neuromuscular training (e.g., spike-specific jump training) is highly advised to volleyball coaches and trainers in order to enhance athletic jump performance. The RSImod could also be adopted to monitor SpJHs as an alternative tool, although with less certainty compared with the RFD. Moreover, we encourage volleyball coaches and trainers to track the changes in concentric net impulse values for predicting athletes' spike jump height, and also to observe the impacts of training programs. Future research is advised to investigate the impact of sports-specific jump strategies on F-T curve characteristics during game-like conditions to precisely determine the requirements for individual types of jumping methods.

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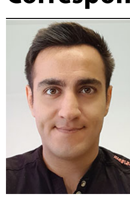

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Compliance with ethical guidelines

Conflict of interest. J. Sarvestan, Z. Svoboda, and J.G. de Oliveira Claudino declare that they have no competing interests.

All studies performed were in accordance with the ethical standards indicated in each case. The approval for this research study was obtained from the ethics committee of Faculty of Physical Culture, Palacky University Olomouc (ethics code: 79/2018).

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Kinematic differences between successful and faulty spikes in young volleyball players

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ABSTRACT
This study was designated to investigate the kinematical differences between successful and faulty spikes, in order to identify the best strategies leading to better spike performance. Simulating a real-game condition, 13 elite youth attackers performed 6 spikes in the presence of 2 blocks. The kinematic variables of the spike performances were recorded using 6 optoelectronic cameras (Vicon Motion systems, Oxford, UK). The paired sample t-test was used to compare the kinematic variables recorded during the delivery of successful and faulty spikes. Among the successful trials, both the angular velocities of the knees (≈12.4%) and hips (≈13.3%), and the vertical velocity of the centre of mass at take-off (≈6.5%) and arm swing (≈8.2%) were considerably higher during the plant phase. Consequently, the jump (≈4.3%) and spike (≈1.5%) heights, as well as the wrist velocity (≈5.5%), were significantly higher during the jump phase of successful spikes. In successful spike performances, the attackers adopted higher hip and knee angular velocities, combined with efficient arm swings, to produce higher take-off velocities and reach higher jump heights. This approach provides them with the better position regarding the ball and the blockers to find the best path and hit the ball with higher arm velocities.

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3D Kinematics Analyses; spike Monitoring; spike Altitude; impact Timing; hip Extension

Introduction

Spikes are the most important technical actions in volleyball and their performance is related to the match success (Fuchs, Menzel et al., 2019; Valadés et al., 2016). High-skilled volleyball players annually execute >40,000 spikes (Serrien, Anders et al., 2016). Therefore, the observation of spike performance mechanics in more detail seems to be essential for the improvement of game performance of volleyball teams. A kinematic analysis of movement changes could be considered as a suitable tool, which leads to a better understanding of spike performance deficits and improvement of training programmes (Serrien, Anders et al., 2016). From the biomechanical point of view spike height, spike velocity, and the ball trajectory path are the main variables determining the spike success rate (Drikos et al., 2009; Fuchs, Fusco et al., 2019; Fuchs, Menzel et al., 2019; Valadés et al., 2016).

The achievement of the highest altitude is considered as one of the main objectives of attackers, because it enables a good view and helps to identify an optimal path for the attack (Fuchs, Menzel et al., 2019). Furthermore, a high jump height corresponds to a relatively long flight time, sufficient for making optimal decision (Cheraghi et al., 2017; Sarvestan et al., 2018; Ziv & Lidor, 2010). In the scientific literature there are many studies focused on volleyball spikes and relationship between jump height and various parameters (e.g., skill level, muscular status) (Fuchs, Menzel et al., 2019; Palao & Valades, 2009; Valadés et al., 2016; Wagner et al., 2009; Ziv & Lidor, 2010). The performance of spikes involves harmonious movements of the lower and upper body extremities, which means an effective segmental sequence of the body segments' movements during the approach and plant phases (Fuchs, Fusco et al., 2019; Fuchs, Menzel et al., 2019).

In the case of plant phase, one of the key elements influencing jump height is the transfer of forward acceleration at the centre of mass (CoM) to vertical acceleration in order to reach higher jump height (Fuchs, Fusco et al., 2019; Serrien, Ooijen et al., 2016; Wagner et al., 2009). It has been shown that this transfer associated with an increase of knee extension velocity $22°.s^{-1}$, would increase jump height for 1 cm in volleyball players (Fuchs, Fusco et al., 2019). Another important variable associated with spike jump height is the arm swing velocity during the plant phase, which describe the ability of the attackers to rapidly flex their arms in the sagittal plane to promote momentum and ground reaction force (Fuchs, Fusco et al., 2019; Serrien, Ooijen et al., 2016). This action is important not only for the increase of spike jump height (10 to 28%), but also for preparation of the attackers' hand to hit the ball at the highest possible altitude (Chiu et al., 2014). Furthermore, the countermovement action of the upper- and lower extremities can stimulate the stretch-shortening-cycle (SSC) of ankle, knee and hip extensors which can result in higher vertical acceleration of CoM (Fuchs, Fusco et al., 2019; Sarvestan, Cheraghi et al., 2019).

The angular momentum, which is generated along the kinetic chain (through the pelvis, trunk, upper arm, forearm, and hand) is also fundamental in the achievement of a higher spike velocity (Fuchs, Fusco et al., 2019; Valadés et al., 2016; Wagner et al., 2014). The velocity of the proximal segments corresponds to the velocity of the distal segments. Finally accumulated tangential velocity in the last segment, is transferred to the ball.

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Scientific studies also confirmed that some technical and coordinative parameters can influence the spike performance (Ferris et al., 1995; Forthomme et al., 2005; Palao & Valades, 2009; Rokito et al., 1998; Valadés et al., 2016; Vint & Hinrichs, 2004).

Previous research investigations have analysed in detail the kinematics and kinetics of spike performance (Fuchs, Fusco et al., 2019; Fuchs, Menzel et al., 2019; Serrien, Anders et al., 2016; Wagner et al., 2009). Nevertheless, to the authors' best knowledge, none of them tried to investigate the differences in the kinematic variables between successful and faulty trials (delivered by elite players), nor identified those that could lead to a better spike performance under simulated match conditions. Thus, this study aimed to identify differences in the kinematics of successful and faulty spikes delivered by young elite volleyball players in a real-game simulation. We hypothesized that take-off velocity, spike jump height, spike height, and spike velocity would be higher in successful spikes in comparison with faulty spikes.

Methods

Participants

Thirteen young elite volleyball players of national level voluntarily participated in this study. Table 1 depicts the demographic and anthropometrical characteristics of the participants. Participants were included Eleven right-handed and two left-handed spikers with opposite dominant leg. In order to avoid the influence of a particular group during the experiment, we included three types of spikers (i.e., wing, middle, and opposite spikers). The selected players had previously participated in international competitions; moreover, during the experiments, they were participating in the national training camp for international U-17 competitions. The players did not report acute injuries during the measurements, and had not claimed any musculoskeletal injuries (e.g., muscle, ligament, or tendon operation; joint dislocation or bone fracture) in the 12 months prior to the measurements. The aims of this study were explicitly explained to the players and their parents signed a written informed consent prior to data sampling. This study was approved by the ethics committee of the Faculty of Physical Culture (Palacky University Olomouc) on the base of the ethics code 79/2018, which is in line with the ethical norms on human experimentation.

Procedures

The participants, including 7 wing spikers, 2 opposite spikers, and 4 middle blockers, were asked to perform 6 spikes in the presence of 2 defenders (1 middle blocker and 1 wing spiker) after a 10-min dynamic warm up, followed by a 10-min volleyball-specific training aimed at reducing the probability of execution-related injuries. The spike movement (attacker) was anticipated by the defenders and they were asked to try to block the attackers as they do in the match condition in order to simulate the game condition. There was no instruction for the spike direction and the attackers were asked to hit the ball into the opponents' court in the desired direction. Given that the spikes were performed in the centre of the playground, the blockers tried to primarily block the forward direction; nevertheless, it did not happen in all performances due to the fact that the defenders' hands moved towards their anticipation of spike direction.

Former studies tried to keep the ball condition constant by attaching it to a rope and leaving it suspended in the air (Wagner et al., 2009). However, the reliability of the spiking performance data collected while applying this technique tends to be lower to that of those collected under real-game conditions (Serrien, Anders et al., 2016). Therefore, a setter, whose skill level was approved by the coaches, was appointed to set the ball with the highest possible accuracy. In order to unify the spike condition, the wing and opposite spikers attacked the ball which was set 1 metre above the setter's head and the middle blockers attacked the ball which was half of a metre above the setter's head. The approach (hitting) direction towards the net was similar among both middle blockers and wing spikers. To be consistent for the setter, the ball was tossed by an experienced coach for all attackers. The attacks were then implemented from any preferred starting point towards the tossed-up ball (Serrien, Anders et al., 2016).

Table 1. Characteristics of participated athletes (n = 13).

Variable	MEAN±SD
Age (year)	15.4 ± 0.72
Height (cm)	190.4 ± 5.76
Weight (kg)	76.2 ± 5.66
Volleyball Experience (year)	6.51 ± 0.7

Marker placement, data recording, and processing

Using the Plug-in-Gait model, 37 passive reflective 14 mm diameter markers were attached to bony landmarks by an experienced researcher of the Vicon® motion analysis system (Oxford Metrics, Oxford, UK) to identify the centre ankle, knee, hip, shoulder, and elbow joints, as well as the position of the body segments (e.g., foot, calf, femur, pelvis, thorax, upper arm, forearm, and head) (Gutierrez-Farewik et al., 2006; Wagner et al., 2009). Six optoelectronic cameras (Vicon Motion systems, Oxford, UK) were also employed to sample the spatiotemporal 3D trajectory of the mentioned markers at the sample rate of 180 Hz for further analyses (Sarvestan & Svoboda, 2019).

Data reconstruction and labelling were conducted adopting the Vicon® Nexus software (Version 1.8.6, Oxford Metrics, Oxford, UK). A gap filling process was performed for the lost markers by applying the pattern and spline methods; moreover, the data smoothing process was conducted applying by a fourth order Butterworth filter (zero-lag) at a cut-off frequency of 10 Hz. In this study, the global coordinate system was defined as the following, the z-axis represented the vertical axis, the y-axis represented the movement orthogonal to the net, and the line under the net represented the x-axis.

Data analysis

As in former studies, the spike action was divided into three phases (i.e., the approaching, plant, and jump phases) in order to analyse in detail the performance of the attackers (Fuchs, Fusco et al., 2019; Wagner et al., 2009). The approaching phase was defined from the onset of the forward movement to the instant of the full contact of both feet, which signals the start of the plant phase (Wagner et al., 2009). The plant phase also defined as the instant of both feet ground contact to take-off (Wagner et al., 2009). The plant phase ended at the instant of take-off (feet leave the ground) and followed by the jump phase. It was ended at the instant of the landing leg touches the ground (Wagner et al., 2009). The movement of the upper extremities (which hit the ball) happens entirely during the jump phase and was also formerly divided into three phases (i.e., the cocking, acceleration, and follow-through phases; Figure 1) (Serrien, Anders et al., 2016; Wagner et al., 2009).

The total body CoM was computed applying a regression formulation on the segment positions (Dempster, 1955). The step length (an approaching phase variable) was computed as the distance between the heel markers (corresponding to the toe-off and the full-contact of the last step) in a sagittal plane (Wagner et al., 2009). The average horizontal velocity of the CoM was calculated as the first derivative of the CoM displacement along the forward direction. The knee and hip angles of the orientation leg (front leg) were calculated considering the relative angles between the shank-femur and the femur-trunk with the positive values for flexion (Wagner et al., 2009). The attacking hand (arm swing-wrist markers of both hands) and CoM vertical velocities were calculated similarly to the CoM horizontal velocity, but along the vertical direction. The Euler angles between the upper arm and the thorax were set and used to calculate the shoulder joint flexion/extension, internal/external rotations, horizontal abduction/adduction, and abduction/adduction angles (B. Serrien Anders et al., 2016). The elbow joint angle was calculated similarly to that of the knee and hip joints, but considering the distance between the forearm and upper arm (B. Serrien Anders et al., 2016). This study considered positive angle directions for the elbow, shoulder, hip, and knee flexions, but negative angle directions for the shoulder and hip hyperextensions. The lower extremity joint angular velocities were defined as the first derivative of the angle-time series of individual joints (Fuchs, Menzel et al., 2019).

Adopting the tangential velocity formula, we calculated the trunk (acromion markers endpoints), shoulder, elbow, and wrist velocities in a sagittal plane (Allen et al., 2010). The moment in which the ball was hit was identified from a sharp decrement in the acceleration of the spiking hand in the Y direction (Serrien, Anders et al., 2016; Wagner et al., 2014). The jump height was calculated as the vertical difference between the maximum and standing CoM values at the static standing position (Serrien, Anders et al., 2016). The average values for kinematic data of successful and faulty spikes were used for subsequent statistical analysis. In successful spikes, the players were able to direct the ball with a wrist tangential velocity of over 50 $km.h^{-1}$ inside the opponents' playground; moreover, these actions were not kill-blocked and no block touch decreased the ball velocity. The trials that touched the blockers' hand and entered to the opponents' playground with high velocities were also considered as successful spikes. Furthermore, the spikes in which the attackers could not lead the ball inside the opponents' playground with high velocities, blocked by defences or the velocity abruptly decreased by block or net touch were counted as faulty spikes (Yamada et al., 2012). The MATLAB software (version 2018b, MathWorks, Inc., Natick, MA, USA) was employed to perform all of the analyses described above for 76 out of the 78 trials (there were post-processing issues with 2 trials of 2 individual attackers).

Statistical analyses

The normality of the data distribution was checked through the Shapiro-Wilk test and the QQ-plot, while the variance homogeneity was analysed employing the Levene's test (Serrien, Anders et al., 2016). Afterwards, the paired sample t-test was applied to identify the differences in the kinematics variables of successful and faulty spikes among attackers. The significance level was set at $\alpha = 0.05$. In order to justify the experimental wise error for the statistical significance, the Holm-Bonferroni corrections were conducted resulting in the adjustment of level of significance for each group of variables as follows: time 0.05/5 = 0.01, length 0.05/3 = 0.017, peak joint angle 0.05/4 = 0.013, angular velocity 0.05/3 = 0.017, and linear velocity 0.05/7 = 0.007. The effect size was estimated using Cohen's d, and the values were interpreted as follows: $d < 0.2$ = small effect size, $0.2 < d < 0.8$ = moderate effect size and $d > 0.8$ = large effect size (Urdan, 2016). The entire statistical analyses were performed using SPSS (version 22.0, IBM Corp., Armonk, NY, USA) and Microsoft excel (version 2016, Microsoft, Redmond, WA, USA) software.

Results

Shapiro-Wilk statistical test demonstrated the normality of data distribution (minimum p value = 0.172). Out of 76 spikes, 46 of them were successful and 30 were faulty (success rate = 60.5%)

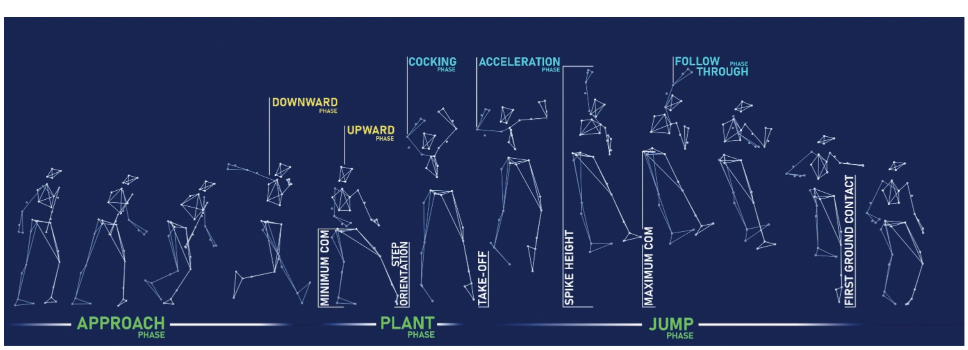

Figure 1. Spike phases for a right-handed spiker.

among all attackers. The success rate was 57% for middle blockers, 60% for wing spikers, and 66% for opposite spikers. The impact location consistency was represented by a maximum difference of 28 cm (mean: 25 ± 3) in the Y-direction, 31 cm (mean: 29 ± 2) in the X-direction, and 24 cm (mean: 21 ± 3) in the Z direction for the middle blockers and 32 cm (mean: 28 ± 4) in the Y-direction, 35 cm (mean: 30 ± 5) in the X-direction, and 21 cm (mean: 18 ± 3) in the Z direction for the wings and opposite spikers.

The Holm-Bonferroni application for multiple comparisons showed significant difference between jump phase durations ($p < 0.01$), where the flight times were significantly more in successful trials. In line with the jump phase, it was also shown that the jump height measures were also more in case of successful trials ($p < 0.017$). The hip angular velocities were also reached to a considerably higher values in successful spikes ($p < 0.017$). Furthermore, the peak vertical COM velocities (Take-off velocities) were significantly higher in successful attacks ($p < 0.007$).

The paired sample T statistical test has shown no significant differences between the variables of the successful and faulty spikes during the approaching phase (Table 2). A first noticeable significant difference was observed at the planting phase, where the vertical velocities of the trunk (which greatly influence the jump height (Sarvestan et al., 2018)) were considerably higher in the case of successful spikes (≈11.9%, $p = 0.042$). Moreover, the extension (angular) velocity of both the orientation leg knee (≈12.4%, $p = 0.024$) and hip (≈13.2%, $p = 0.004$) joints were significantly higher during successful trials during the plant phase.

The CoM_V velocity at the moment of take-off was significantly higher in the case of successful spikes (≈6.5%, $p = 0.007$). Additionally, following the increase in the vertical velocities of the CoM, trunk and arm swing (≈8.2%, $p = 0.028$), the jump (≈4.3%, $p = 0.046$) and spike (≈1.5%, $p = 0.026$) heights were also higher in this case. As expected, higher take-off velocities provided the players with significantly longer jumping phases (of 0.04 s, $p = 0.002$) during which they could perform the spike. Spike velocity (wrist velocity here), one of the key factors in scoring points, was also considerably higher in the case of successful spikes (≈6.5%, $p = 0.025$); meanwhile, no significant differences were observed in the elbow and shoulder velocities.

Figure 2 portrays the differences in knee flexion/extension, the hip flexion/extension, the shoulder horizontal abduction/adduction, and the elbow flexion/extension joint angle differences for successful and faulty spikes among all attackers. Although the knee and hip angular patterns were similar for successful and faulty spikes, they showed different angular displacements during the approach phase (during the orientation of the leg). The dominant shoulder joint showed no significant horizontal abduction in the case successful trials. Similarly, the dominant elbow angles experienced no noticeable different among both cases.

Discussion

In volleyball, the attack success rate is directly correlated with the success of a match (Valadés et al., 2016; Vint & Hinrichs, 2004). Numerous research studies have investigated the kinetics and kinematics of volleyball spikes, considering the jump height, spike velocity, and ball trajectory path as key elements related to the spike success (Fuchs, Menzel et al., 2019; J. Palao et al., 2004; J. M. Palao & Valades, 2009; Valadés et al., 2016). This study was designated to analyse the kinematical changes that lead to successful spike performances among young elite volleyball players. The deficits in spike performance can be first identified during the plant phase: the players demonstrated higher values of trunk velocities, accompanied by higher arm swing, the knee and hip extension velocities in the case of successful tries, which distinguished with a meaningfully high effect size. These resulted in a considerably higher take-off (here CoM_V) velocities, and consequently, the jump, and spike heights were significantly higher in the case of successful spikes, and the players had more time to perform their spikes due to longer flight time.

Table 2. Differences in the kinematic parameters of faulty and successful spikes among all attackers.

Variable		Successful	Fault	Sig. (2-tailed)	t	CI	Cohen's d
TIME (s)	Approach Phase Duration	0.54 ± 0.03	0.54 ± 0.02	0.851	−0.07	[−1.87,1.87]	0.00
	Planting Phase Duration	0.22 ± 0.01	0.22 ± 0.03	0.903	0.03	[−1.87,1.87]	0.00
	Jump Phase Duration	0.70 ± 0.05	0.66 ± 0.07	0.002‡	−5.73	[−1.77,0.46]	0.66
	Total Spike Duration	1.47 ± 0.03	1.41 ± 0.06	0.014†	−4.12	[−2.46,-0.07]	1.27
	Peak COM Height to Spike	0.013 ± 0.006	0.015 ± 0.004	0.378	0.72	[−0.71,1.49]	0.39
LENGTH (cm)	Step Length	201.5 ± 16.41	202.1 ± 15.24	0.928	0.01	[−1.05,1.13]	0.04
	Jump Height	78.54 ± 4.25	75.14 ± 5.12	0.005‡	−2.07	[−1.85,0.41]	0.72
	Spike Height	303.49 ± 6.87	299.14 ± 6.38	0.026†	−3.46	[−1.77,0.46]	0.66
PEAK JOINT ANGLE (°)	Peak Knee Flexion	104.34 ± 8.65	103.99 ± 7.16	0.865	−0.06	[−1.13,1.04]	0.05
	Peak Hip Flexion	75.06 ± 4.52	73.63 ± 5.61	0.071	−1.49	[−1.35,0.84]	0.26
	Max Shoulder Horizontal Abduction	87.21 ± 6.83	86.95 ± 7.54	0.725	−0.15	[−1.12,1.05]	0.04
	Max Shoulder Hyperextension	156.41 ± 12.58	155.83 ± 10.47	0.692	0.22	[−1.14,1.04]	0.05
ANGULAR VELOCITY ($°.s^{-1}$)	Peak Front Leg Ankle Velocity	981 ± 118	962 ± 103	0.486	0.51	[−1.26,0.92]	0.17
	Peak Front Leg Knee Velocity	1121 ± 156	982 ± 107	0.024†	−3.53	[−2.20,0.12]	1.04
	Peak Hip Velocity	1053 ± 179	914 ± 129	0.004‡	−5.32	[−2.03,0.25]	0.89
LINEAR VELOCITY ($km.h^{-1}$)	Peak COM_H Velocity	12.47 ± 1.57	12.18 ± 1.14	0.594	−0.37	[−1.30,0.88]	0.21
	Peak COM_V Velocity	13.28 ± 1.62	12.42 ± 1.25	0.007‡	−4.96	[−1.71,0.52]	0.59
	Arm Swing Velocity at Take-Off	38.12 ± 3.72	34.99 ± 3.83	0.028†	−3.39	[−1.96,0.30]	0.83
	Peak Trunk Velocity at Take-Off	22.75 ± 2.53	20.06 ± 2.71	0.042†	−2.48	[−2.18,0.13]	1.03
	Peak Wrist Velocity	62.66 ± 4.17	59.24 ± 5.84	0.025†	−3.49	[−1.79,0.44]	0.67
	Peak Elbow Velocity	36.51 ± 4.94	36.07 ± 5.13	0.685	0.24	[−1.17,1.00]	0.09
	Peak Shoulder Velocity	18.42 ± 2.07	18.17 ± 1.84	0.792	0.12	[−1.22,0.96]	0.13

†Significant at $p < 0.05$.
‡Significant at $p < 0.01$.

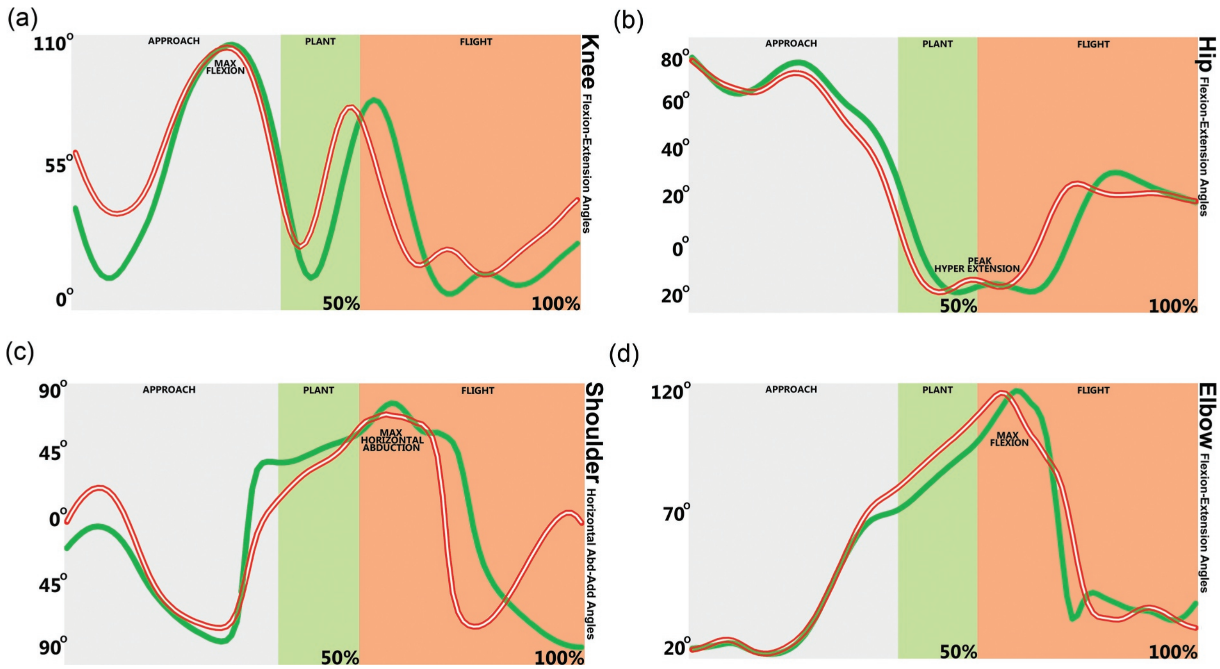

Figure 2. Angle-time series of (a) orientation leg knee flexion-extension, (b) orientation leg hip flexion-extension, (c) dominant shoulder horizontal abduction-adduction, and d) dominant elbow flexion-extension in the case of successful and faulty spikes. The red double line and the green line represent the faulty and successful spikes, respectively.

The spike velocity, directly related to performance, was also higher in this case. Nevertheless, prior to further interpretations, it must be noticed that the Bonferroni-Holm corrected multiple comparisons showed no significant effect among all variables, except the jump phase duration.

It has been formerly pointed out that the orientation step length, the main factor contributing to the CoM horizontal velocity, does not have any relationship with the jump height (Fuchs, Fusco et al., 2019; Ikeda et al., 2018); nonetheless, the CoM horizontal velocity could increase following an elongation of the step length (Fuchs, Fusco et al., 2019). The results of this study also demonstrated that, during the approach phase, no significant differences existed in the step lengths and peak CoM horizontal velocities of successful and faulty spikes. These indifferences, furthermore, resulted in approximately similar approaching phase duration in both successful and faulty spikes. Therefore, it could be claimed that the strategy adopted by the attackers during the approaching phase does not seem to be an indicator of the spike success rate.

It has been previously proposed that the maximum angular velocity of the orientation leg knee joint is one of the key factors (>80% of contribution) determining the jump height in volleyball (Fuchs, Fusco et al., 2019). This variable (which is associated with the lower limbs' power and strength and depends on the coordination ability) is directly related to the explosive strength of the lower limbs' muscles (Copic et al., 2014; Sarvestan et al., 2018). In line with those studies, we proved that angular velocities of the orientation leg knee and hip joints (with considerably high effect size values) were high in the case of successful spikes. Since the same attacker experienced both successful and faulty spikes, it could be stated that the rate of knee and hip extensor muscles contraction were higher in successful trials. Although this time point appeared to have been the first stage of motor impairment, a look at previous movement frames revealed that the hip flexion angles were significantly higher in the case of successful spikes. Theoretically, based on the concept of SSC (i.e., the capability of muscle groups to have a rapid concentric contraction immediately after an eccentric contraction (Komi, 2003; Nicol et al., 2006)) and due to the observed kinematics from hip angles, we can infer that the players flexed their hip joints more; this movement resulted in a particularly rapid activation of the muscle spindles and overwrote the function of Golgi tendon organ of the hip extensors, as well as in a sharply increase of the hip joint's angular velocity. This approach could help the players achieve a greater produced momentum in the trunk, which could aid in higher jump heights during the spike. Nevertheless, this interpreting must be taken with caution given that we did not use the electromyography and only made the conclusion based on the kinematics outcomes.

The arm swing-produced momentum that is thought to increase the jump height during the plant phase (by 10%–28%) and the take-off velocity (by 72%), especially if it is used in the harmonious movement of a proximal-to-distal sequence (Chiu et al., 2014; Fuchs, Fusco et al., 2019; Lees et al., 2004; Sarvestan, Cheraghi et al., 2019). Theoretically, an upward acceleration of the upper extremities produces a downward momentum through the CoM, consequently increasing the vertical impulse of the CoM (Lees et al., 2004). During the successful spikes, the players adopted this strategy: they increased the arm swing velocity in order to exploit the momentum in their jump, and this strategy ultimately helped in significantly higher CoM vertical velocities at take-off. The CoM vertical velocity was the principal factor inducing high jump altitudes (see the use of this variable for the calculation of the jump height (Pérez-Castilla et al., 2017; Sarvestan et al., 2018). The application of this strategy resulted in significantly higher jump and spike altitudes during the jump phase, followed by considerably higher flight times, in the case of successful trials. Overall, these mechanisms provide the player with the ability of controlling the spike position, the ball trajectory over the opponents playground, and of choosing the best possible moment to hit the ball (Fuchs, Fusco et al., 2019; Fuchs, Menzel et al., 2019; Valadés et al., 2016). Although several factors, including the block failure or ball set, might limit the attackers' option for choosing the best time for hitting the ball, we controlled the block position and impact location for the entire trials in order to decrease the external interferers and only observed the attackers' performance independently.

The transfer of the proximal-to-distal momentum has been found to amplify the arm movement performance in throwing or hitting sports (Serrien et al., 2018; Wagner et al., 2011, 2014). One of the strategies employed to maximize the muscular performance over a short period of time is the activation of the SSC feature of the muscle groups (Cormie et al., 2010; Komi, 2003; Sarvestan, Riedel et al., 2019). The horizontal abduction of the shoulder joint activates the SSC function of the shoulder horizontal adductors and internal rotators; however, during the cocking phase of the jump, no significant differences were observed in the maximum angles of shoulder horizontal abduction under both conditions. These results indicate that the arm movement is not affected at all by jump or spike height deficits. Considering a similar horizontal abduction for the shoulder, we observed that the tangential velocities of the trunk and elbows were similar under both conditions. Interestingly, the wrist velocity (represented by the spike velocity at the impact moment), was significantly lower in the case of faulty spikes. Such an abrupt decrease in wrist velocity could be related to the several reasons: lower jump heights, spike heights and to the flight times. Usually, volleyball players make their final decision in the shortest time span possible before the impact moment. We noticed that successful spikes were performed when the players were provided with a better view over the opponents' playground and more flight time: under these circumstances, they were able to make the best decision and perform the spikes in more time and a wider vision.

Furthermore, by focusing on the time interval between the achievement of the maximum CoM and the impact moment, we also noticed that the players hit the ball slightly sooner after reaching the highest CoM altitude during successful trials: they were able to choose among more possibilities due to the higher altitude and longer flight time. Meanwhile, a delay in the achievement of the maximum CoM height and of the impact moment, which apparently took place due to lower jump and spike heights, caused a significant decrease in the spike velocity, resulting in a faulty spike. In fact, a shorter jump height, originated by the decrease in spike velocity, lowered the possibilities of choosing the best possible option; meanwhile, in this situation the blockers were also able to easily anticipate the ball path and counter it.

Limitations

Due to the hardness of attachment of hand markers during spike, we calculated the spike velocity from the wrist velocity at the impact moment, which could represent lower amounts of velocities compared with the hand or ball velocities. Nevertheless, given that we compared these velocities in both successful and faulty conditions, both numbers compared from similar markers. Besides, the trajectory of spiked ball was not controlled in this study, since the players were structured to just hit the ball inside the playground. This could be of the other limitations of this study, given that different strategy adopted for leading the ball to the opponent's playground might lead to different kinematical differences during the flight phase, regardless of the success rate

In this study, we detected 2 blockers to counter the attackers' spike. Since both blockers will rarely be able to stand and wait in front of the attacker (given that the middle blocker moving with the attacker and the wing blocker joint the middle by using side shuffle or swing block to stop the attack) during the real game, the condition provided for the attackers might not 100% representing the real game condition.

Conclusion

The findings of this study indicated that, regardless of the skill level and strength of the defenders, a sequence of movement deficits reflected by the kinematic variables (e.g., lower hip and knee angular velocities during extension, jump and spike heights, and spike velocity) is the main reason behind the poor spike performance of attackers. Hence, regardless of blocks' impact, volleyball players should aim at enhancing their spike performance coordination, which can be attained under various real-game simulated conditions by practicing harmonious spatiotemporal movements of the neuro-musculoskeletal system. This study, further confirms that higher angular velocities of the hip and knee joints, combined with an efficient employment of the arm swing, can increase the jump height during the performance of spikes in a real-game situation. Nonetheless, the spike velocity is influenced by several situation-specific parameters (e.g., the velocity and position of the tossed ball in the air) that might completely change the players' performance.

Disclosure statement

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Article

Analysis of Whole-Body Coordination Patterning in Successful and Faulty Spikes Using Self-Organising Map-Based Cluster Analysis: A Secondary Analysis

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Abstract: This study investigated the whole-body coordination patterning in successful and faulty spikes using self-organising map-based cluster analysis. Ten young, elite volleyball players (aged 15.5 ± 0.7 years) performed 60 volleyball spikes in a real-game environment. Adopting the cluster analysis, based on a self-organising map, whole-body coordination patterning was explored between successful and faulty spikes of individual players. The self-organising maps (SOMs) portrayed whole body, lower and upper limb coordination dissimilarities during the jump phase and the ball impact phases between the successful and faulty spikes. The cluster analysis illustrated that the whole body, upper limb and lower limb coordination patterning of each individual's successful spikes were similar to their faulty spikes. Range of motion patterning also demonstrated no differences in kinematics between spike outcomes. Further, the upper limb angular velocity patterning of the players' successful/faulty spikes were similar. The SPM analysis portrayed significant differences between the normalized upper limb angular velocities from 35% to 45% and from 76% to 100% of the spike movement. Although the lower limb angular velocities are vital for achieving higher jumps in volleyball spikes, the results of this study portrayed that the upper limb angular velocities distinguish the differences between successful and faulty spikes among the attackers. This confirms the fact that volleyball coaches should shift their focus toward the upper limb velocity and coordination training for higher success rates in spiking for volleyball attackers.

Keywords: SOM; angular velocity; coordination; volleyball spike; unsupervised machine learning

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1. Introduction

Success in volleyball competitions is directly related to the attacking capabilities of the offensive players [1]. Spikes, as the second and the most important attacking tool, play a pivotal role in this success rate. A successful attack demands highly coordinated actions of the neuromuscular system [2]. Various physical (e.g., strength, coordination) and psychological attributes (e.g., game pressure, scores) underpin success rates in the volleyball spike [3–5]. Kinematic analysis of successful spike performance has highlighted movement patterns that result in a faulty spike [1]. Nevertheless, a more sophisticated analysis assessing multiple segment interaction could pave the way for a better understanding of underlying mechanisms that contribute to a better spike performance, particularly during competition [1,6].

Several studies have biomechanically investigated the volleyball spike among elite and sub-elite male and female volleyball attackers [2,7–10]. Wagner, Tilp [11] endorsed that approach velocity, knee angle, and arm swing are principal factors for a more effective spike performance. Serrien, Ooijen [12] highlighted a significant difference between trunk lateral and sagittal tilt, and rotational velocities, pelvis sagittal tilt velocities, and shoulder horizontal abduction and internal rotation velocities between elite and sub-elite male and sub-elite female volleyball players. Fuchs, Menzel [6] demonstrated that jump height, approach speed, step length, mean lower limb muscle activation, and net impulse are significantly higher in elite male players compared with elite female players. More recently, Sarvestan, Svoboda [1] claimed that the volleyball players produce significantly more knee and hip extension angular velocities, take-off velocities, arm-swings, jump and spike heights, and impact velocities in successful spikes compared with faulty spikes. Despite this evidence base, it is still not clear how the multiple kinematic degrees of freedoms (DOF) are integrated to produce an accurate and efficient movement pattern in the volleyball spike.

According to dynamical systems theory, motor performance continually adapts to environmental and intrinsic constraints, organising the DOFs for efficient movement execution in a coordinated fashion [13]. In research carried out by Serrien, Ooijen [2] using self-organising maps (SOMs), an arbitrary Euclidean distance was employed to analyse coordination variability. Results demonstrated significantly higher coordination variability (a less stabile coordination patterning) in female volleyball spikers compared with the males. In a similar study investigating the proximal-to-distal coordination in young elite volleyball players using SOMs, Serrien, Goossens [14] showed that sex may be a large contributor to coordination variability, whilst maturation seemingly had no significant impact. SOMs, which are generally considered a class of artificial neural networks, are a concurrent approach being applied to investigate human movement [15]. Within the field of human movement sciences, these SOMs are adopted to explore complex movement patterns in sporting activities [2,16]. This machine learning-based approach could reduce dimensionality and aid in ease of interpretation of multiple-segment coordination patterning [16]. Currently, using the SOMs-based cluster analysis, Sarvestan, Svoboda [16] claimed that whole-body coordination patterning is an individually specific characteristic that remains relatively stable under different task constraints during volleyball spikes among attackers.

Although an abundance of empirical investigations have analysed various kinematic aspects of the volleyball spike using various analytical methods, to date no study has been conducted to assess the whole-body coordination patterning in successful and faulty volleyball spikes. More detailed analytical methods would provide the necessary detail to accurately identify differences in a player's body as a whole which would provide beneficial insight on overall performance. This could also help with sport-specific training, allowing coaches to design a multi-functional training program that targets multi-segment skill development as a whole. To this end, the main aim of this study was to investigate whole-body coordination patterning in successful and faulty spikes among young elite volleyball attackers using SOM-based cluster analysis. We hypothesised that there would be a significant difference between the coordination patterning of successful and faulty spikes.

2. Materials and Methods

2.1. Participants

A total of 13 young elite male attackers (Czech Republic national youth players) participated in this study, however only data for 10 players were included due to issues with data reconstruction. Table 1 demonstrates the general characteristics of included participants ($n = 10$). These consisted of six wing spikers, three middle blockers, and one opposite spiker. Across the participants, two were left-handed spikers (participant 2, wing spiker and participant 4, opposite spiker). Upon attending the laboratory, no acute injuries were reported by the attackers, and no players reported any musculoskeletal injuries or surgery within the last 12 months. Prior to any measures being taken, the purpose of the study and the risks of injuries were thoroughly explained to the participants, and both the players and their head coach signed informed consent forms.

Table 1. General characteristics of the participants.

Variable	Mean ± SD
Age (year)	15.5 ± 0.7
Height (cm)	192.9 ± 4.1
Weight (Kg)	76.9 ± 4.7
Experience (year)	6.9 ± 0.7

2.2. Instrument and Procedure

Following a supervised 15-min dynamic warm-up by the researcher and coaches, the players performed six spikes as part of a sport-specific warm-up. A total of 37 retro-reflective, 14mm-diameter markers were attached to bony anatomical landmarks (head, C7, right scapula, T10, clavicle, sternal notch, acromion, upper arms, lateral humeral epicondyles, forearms, ulnar and radial styloid processes, anterior superior iliac spine, posterior superior iliac spine, thighs, lateral femoral epicondyle, tibia, Lateral malleoli, 1st metatarsal and heels) by a single researcher using the PlugInGait full-body model. Following marker placement, each attacker executed six spikes with the presence of two blockers from an individually chosen starting point. Six optoelectronic Vicon® motion capture cameras (MX13+, Oxford Metrics, Oxford, UK) recorded the trajectories of all markers at a sampling frequency of 180 Hz. The global reference frames were defined as Z-axis (positive) in the upward direction, Y-axis in the anteroposterior direction (forward-positive) and X-axis in the mediolateral direction (right-positive).

Although the volleyball spike has formerly been investigated with the ball set in place using ropes at a specific location [11], we aimed to simulate real-game conditions by using an expert 'setter' to place the ball for the attackers. Therefore, the coach checked the accuracy of the setter and any inaccurate 'set' was repeated. Of the entire 60 sets, only one error, whereby the ball slipped from the setter's hands, was observed and repeated. Furthermore, to check the within-subject impact location consistency, the locations of the wrist markers (ulnar and radial styloid process markers) were assessed at the moment of impact.

2.3. Data Processing and Analysis

Data reconstruction and marker labelling was conducted using Vicon® Nexus software (Version 1.8.6, Oxford Metrics, Oxford, UK). After filling any missed markers using spline and pattern methods (less than 10 missed frames), a 4th order Butterworth filter (0-lag) was used with a cut-off frequency of 10 Hz applied to smooth the trajectories and remove noise [17]. The corresponding static trial's marker set was used to define joints, anatomically offset joint angles, and to locate each segment's centre of mass [18,19]. Joint angles were calculated using the relative orientations of two adjacent segments (for flexion/extension, abduction/adduction, and external/internal rotation) [16]. Adopting the central difference method, the corresponding joint angular velocities were computed. Table 2 represents the kinematic variables used in the coordination patterning analyses. Note that both left and right limbs were incorporated into the analysis.

The time-series data of each spiking trial were first trimmed from the start of the plant phase to the moment of impacting the ball [20], which were then linearly interpolated to 101 data points. The plant phase was identified as the first frame that both feet made ground contact, and ball impact was identified as when the spiking hand wrist markers' acceleration abruptly decreased in the Y-direction [16]. In this study, faulty spikes were defined as in Sarvestan, Svoboda [1], where the attacker was blocked, the spike velocity was lower than 50 $Km{\cdot}h^{-1}$, the ball touched the blocks and its velocity decreased to lower than 50 $Km{\cdot}h^{-1}$, or it touched outside of the area of play. The mean of successful and faulty spikes of individual participants was calculated and used for the SOM and cluster analysis.

Table 2. Overview of kinematic variables used in the self-organising map (SOM) coordination profile analysis.

Joint/Segment	Abbreviations	Descriptions
centre-of-mass	CoMX, CoMY, CoMZ	3D coordinates of the total-body centre of mass
Left and right lower limb joints	LhipX, LkneeX, LankleX RhipX, RkneeX, RankleX	Flexion-extension angles of the hip, knee, and ankle joints
Left and right upper limb joints	LshoulderX, LshoulderY, LshoulderZ, LelbowX RshoulderX, RshoulderY, RshoulderZ, RelbowX	Shoulder ab/adduction, horizontal ab/adduction and internal/external rotation, elbow flexion-extension
Trunk	PelvisX, PelvisY, PelvisZ SpineX, SpineY, SpineZ ThoraxX, ThoraxY, ThoraxZ	Pelvis tilt, obliquity, and rotation (absolute) Spine flexion/extension, lateral flexion, and rotation (relative) Thorax tilt, obliquity, and rotation (absolute)
Neck and head	NeckX, NeckY, NeckZ HeadX, HeadY, HeadZ	Neck flexion/extension, lateral flexion, and rotation (relative) Head tilt, obliquity, and rotation (absolute)

For the computation of whole body, lower limb, and upper limb coordination patterning, as well as joint range of motions (ROM) and angular velocities, we adopted SOMs [21]. The SOM, on the whole, is a 2D grid of weighted units, which are the prototype patterns of the input vectors. In this study, the adopted input vectors are a collection of kinematic variables at each time point:

$$vi(t) = [\psi i,1(t) \ldots \psi i,32(t)\ \varphi i,1(t) \ldots \varphi i,32(t)]t \quad (1)$$

where ψk and φk, respectively, portray the degrees of freedom and the corresponding velocities (k = 1, . . . , 32; see Table 2). The i index is representative of the mean of all participants' spikes (i = 1, . . . , 19); the number of spikes, i.e., 19 was determined as two trials per participant, minus faulty spikes for participant 2 (who did not fault during data collection). Prior to training the SOMs, the input vectors were normalised to −1 to 1 range intervals in order to unify the large kinematic differences between participants [21]. Thereafter, using competition and cooperation across the weight vectors, the SOMs iteratively updated the conversely stabilised solution via a self-organising process [21]. This process involved the Gaussian neighbourhood, hexagonal lattice, and sequential training types in a big map size. Table 3 summarises the parameters applied to the SOM and cluster analyses in this study.

Table 3. Parameters explored in the sensitivity analysis. Applied options in the result section of this study are in bold.

SOM Parameters	Options			
Map size	Small (1/4× default)	Normal (default)	**Big (4× default)**	
Neighbourhood	**Gaussian**	Cut-off Gaussian	Bubble	Epanechicov
Lattice	**Hexagonal**	Rectangular		
Training type	**Sequential**	Batch		

Cluster Linkage Algorithm					
Single	Complete	**Average**	Median	Centroid	Ward's

The adopted training method resulted in a hexagonal grid of units with every two neighbored hexagons having the most coordination state similarities. Since the SOM training adopts the entire successful and faulty spike performances, every two SOM panels demonstrate unified distance matrix (U-matrix) in whole body, lower, and upper limbs. Then, to detect the best-matching unit (BMU), the weight vectors with the smallest Euclidean distances were identified and unified. In the final step of the SOM, a pair-wise distance matrix was composed from the average of the entire coordination patterns by the trained SOM:

$$D_{i,j} = \sum_{t=0}^{100} \left[BMU_i(t) - BMU_j(t)\right]^2,\ i,\ j = 1, \ldots, 19. \quad (2)$$

In the current study, the average data of the successful and faulty spikes were used for every player, except participant 2 as mentioned. Since they recorded only one faulty spike and the data of his faulty spike was removed in post-processing analysis of SOMs (due to technical complications), we used the average of all of their five successful trials.

In order to analyse the inter-individual coordination patterning of joint ROM and angular velocities in both successful and faulty spikes, we used cluster analysis on the matrixes derived from the SOMs. The 'average linkage algorithm' (see Table 3) was used to construct the hierarchical agglomerative clustering for every SOM. Thereafter, a dendrogram was created to represent the mean of trials per participant. Although we applied the cluster analysis for every SOM, only those with considerable differences from whole-body coordination patenting are presented in the results. All data processing and analysis, including the data reduction, interpolation, SOM analysis (SOM Toolbox) and clustering, were conducted using MATLAB software (Version 2020a, MathWorks, Inc., Natick, MA, USA).

2.4. Statistical Analysis

Since this study adopted an exploratory analysis approach where there were observable differences between the coordination, ROM, and angular velocity patterning, the spm1d statistical package (v0.4.3) (www.spm1d.org accessed on 10 February 2021) was used to identify significant differences of BMU trajectories between successful and faulty spikes. Following assessments of normality of data distribution using a Shapiro-Wilk's test, the independent sample T-test (1d_ttest) was employed and significant differences were reported where observed. An alpha value of 0.05 was set a-priori.

3. Results

Within-subject consistency impact locations were checked, and the maximum differences were 10 cm in the mediolateral direction, 16 cm in anteroposterior and 7 cm in the vertical direction. The SOMs, individual BMU trajectories, and cluster analysis of whole-body coordination patterning are depicted in Figure 1. Each hexagonal cell in the U-matrix indicates the Euclidian distance between the neighbouring SOM units. The colour of each unit also represents the average distance between the surrounding neighbor SOM units. The neighbours with fewer distances (blue cells) are also separated by the highly distanced cells (yellow cells). The green ridges have greater neighbouring distances than blue ridges and less neighbouring distances than yellow ridges. In this analysis, we depicted individual BMU trajectories in different colours (but matched in faulty and successful trials) to identify the similarities of successful and faulty pairs for each attacker. The average coordination patterning of successful and faulty spikes for all participants are presented in black BMU trajectories. Every BMU trajectory begins with the plant phase at the top and finishes with ball impact in the bottom of the SOMs.

The panels of Figure 1a identify two big differences on the left and bottom-right edges of the SOMs, specifically where the average coordination patterning is close to the yellow ridges (representing larger neighbouring distances). This portrays that the coordination patterning of successful and faulty spikes is particularly different at the initiation of spike performance where the participant starts to jump. Each pattern that is distinctly placed inside each of these two parts is significantly different from other patterns within the two ridges (near centre). Accordingly, only the initiation of the movement (the plant phase before jumping) and final phase (the cocking phase to impact event) for participants 8 are shown to be different from all other coordination patterning trajectories of attackers (Figure 1a, yellow line from the middle-left edge to the bottom-right edge). Individual BMU trajectories (Figure 1) revealed that every participant has a unique coordination pattern, both in successful and faulty spikes. However, there are differences between the whole-body coordination patterning of successful and faulty spikes between every attacker, particularly in the early and late phases of the volleyball spike. On the whole, the average BMU trajectories, both for successful and faulty spikes, demonstrate different coordination patterning of the whole body in the middle of the movement (Figure 1a, black line in top-right edge). Nevertheless, hierarchical clustering of the coordination patterning in SOMs confirms the similarities between the observed BMU trajectories of successful and faulty spikes between individual attackers. A unique coordination patterning was assigned to each attacker, whereby the BMU trajectories in successful spikes had the most similarities with the faulty trials of a similar attacker. Across individuals, participant 6 had the most similar coordination patterning between successful and faulty spikes (Figure 1a–c, green BMU trajectories), while participant 8 displayed the biggest differences in coordination patterning between successful and faulty trials (Figure 1a–c, white BMU trajectories). In addition, the coordination patterning of participants 2 and 4 was different to the rest of the attackers (levels of coordination dissimilarity $> 8 \times 104$), while participants 3 and 5 had the most similar coordination patterning (levels of coordination dissimilarity $< 2 \times 104$).

As Figure 1b represents, the mean lower limb coordinating patterning (black trajectories) was almost identical when comparing successful and faulty trials. However, this patterning was different between the successful and faulty trials of participant 7 (cyan trajectories). This was also identified by the cluster analysis, where the lower limb coordination patterning of the successful and faulty trials had the least similarities with other attackers.

Analysis for the whole-body and lower limb ROM illustrated similar mean pattern for all attackers. In addition, the cluster analysis revealed similar results to the whole-body and upper limb coordination patterning across individuals (Figure 2a–c). Nevertheless, there are considerable differences between the average ROM patterns of upper limbs during the jump phase, where the black trajectories moved toward yellow ridges with high neighbouring distances in successful spikes. The cluster analysis of upper limb ROM was similar to the upper limb coordination pattern. A different pattern, however, is demonstrated with the upper-limb joint angular velocities (Figure 3c). Furthermore, although the whole-body and lower limb joint angular velocities are shown to have relatively different patterns, the cluster analysis depicted similar results as the patterning (Figure 3a,b).

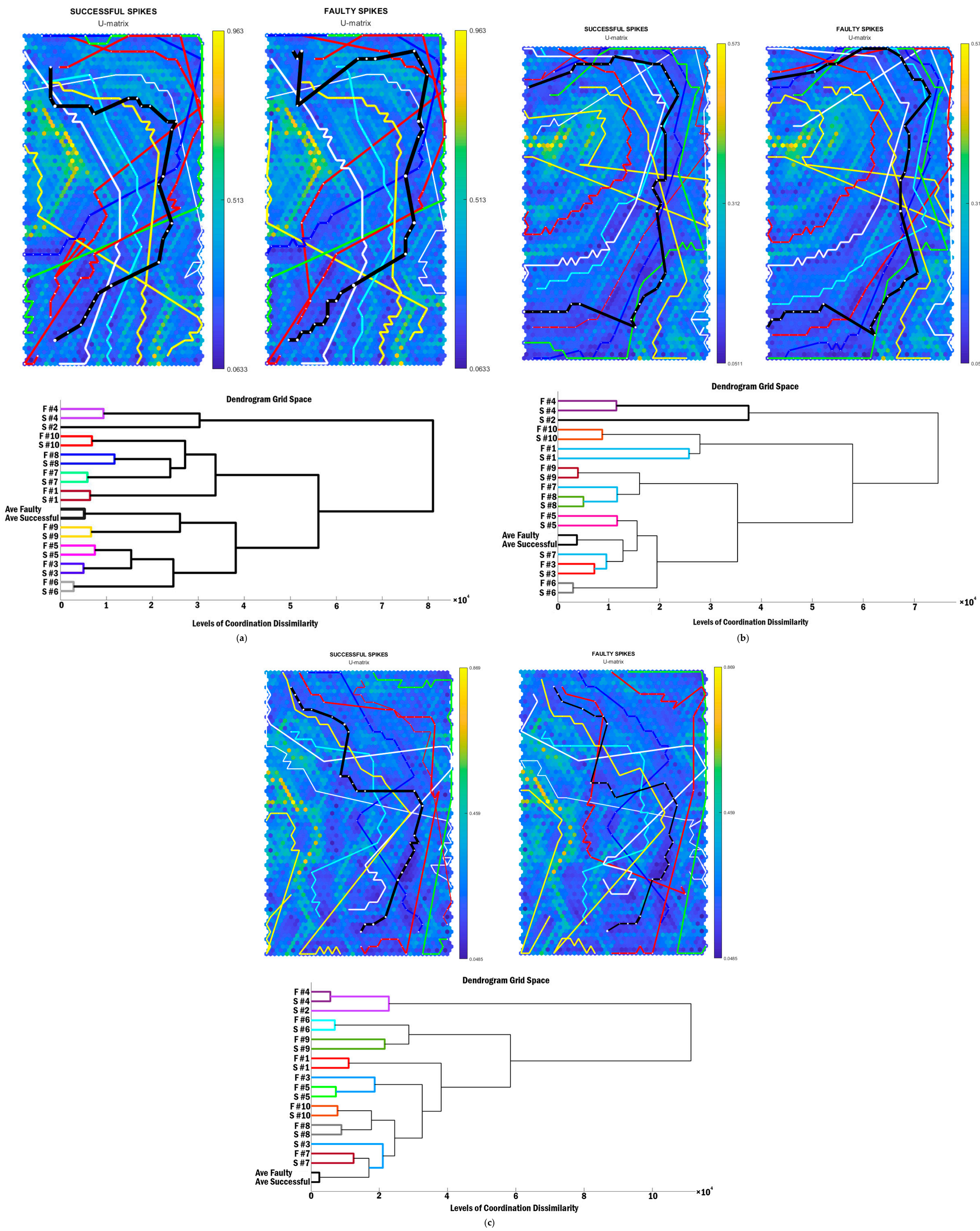

Figure 1. SOMs and cluster analysis of (**a**) whole-body coordination pattern, (**b**) lower limb coordination pattern, and (**c**) upper limb coordination patterning among the attackers. BMU trajectories of individual attackers (identified as a single-coloured line per individual) and the mean coordination patterning (black lines, or trajectories) in successful and faulty spike performances in each SOM. The orange-to-yellow colour of the hexagonal background depicts large Euclidean distance, while the blue colour depicts a small Euclidean distance.

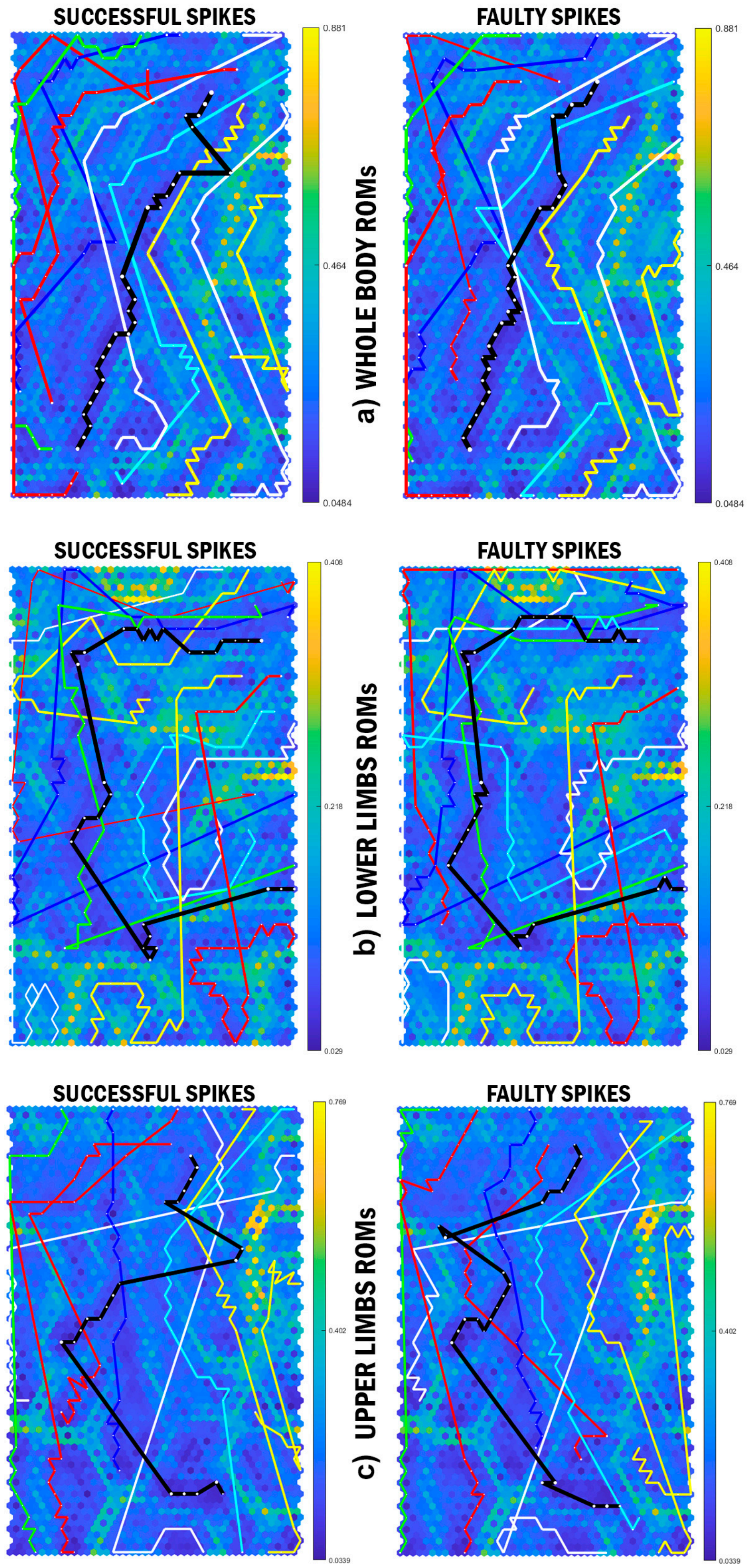

Figure 2. SOMs of (**a**) whole body, (**b**) lower limb, and (**c**) upper limb range of motions (ROM) of the attackers. BMU trajectories of individual attackers (identified as a single-coloured line per individual) and the mean coordination patterning (black lines, or trajectories) in successful and faulty spike performances in each SOM. The orange-to-yellow colour of the hexagonal background depicts large Euclidean distance, while the blue colour depicts a small Euclidean distance.

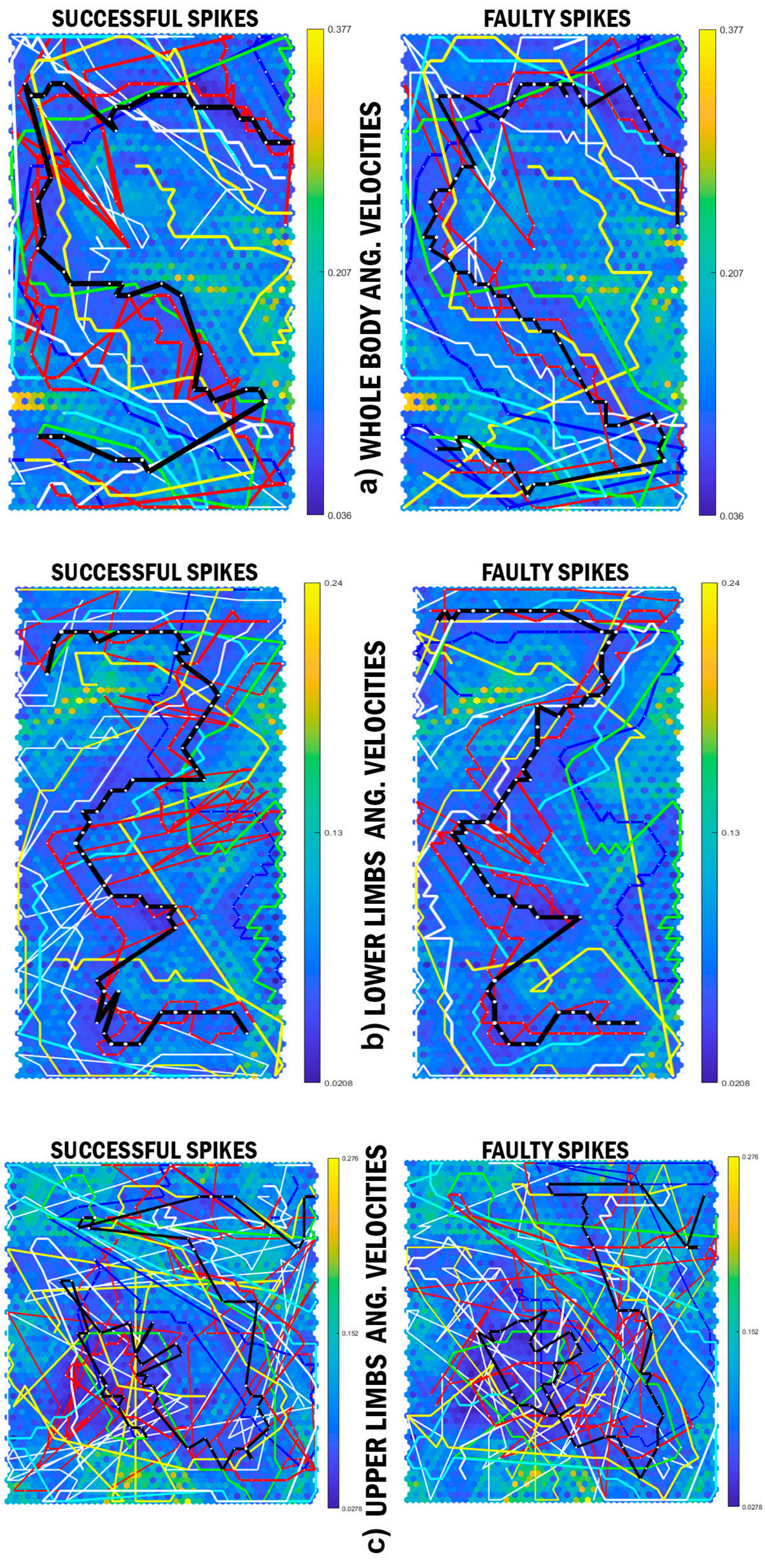

Figure 3. The SOMs of (**a**) whole body, (**b**) lower limbs, and (**c**) upper limb angular velocities among the attackers. BMU trajectories of individual attackers (identified as a single-coloured line per individual) and the mean coordination patterning (black lines, or trajectories) in successful and faulty spike performances in each SOM. The orange-to-yellow colour of the hexagonal background depicts large Euclidean distance, while the blue colour depicts a small Euclidean distance.

The SPM analysis showed no significant differences between the whole body and lower limb joint angular velocities throughout the spike performance. In contrast, the upper limb angular velocities were significantly different between successful and faulty spikes, from 35% to 45% and 76% to 100% of the spike performance (Figure 4b). The cluster and SPM analyses confirmed this with the inter-individual similarities between the upper limb angular velocities in successful and faulty spikes (Figure 4a). Although the average upper limb angular velocities pattern of successful and faulty spikes remained similar, the dissimilarity levels were considerably high compared with the other average pattern (levels of coordination dissimilarity = 2 × 104).

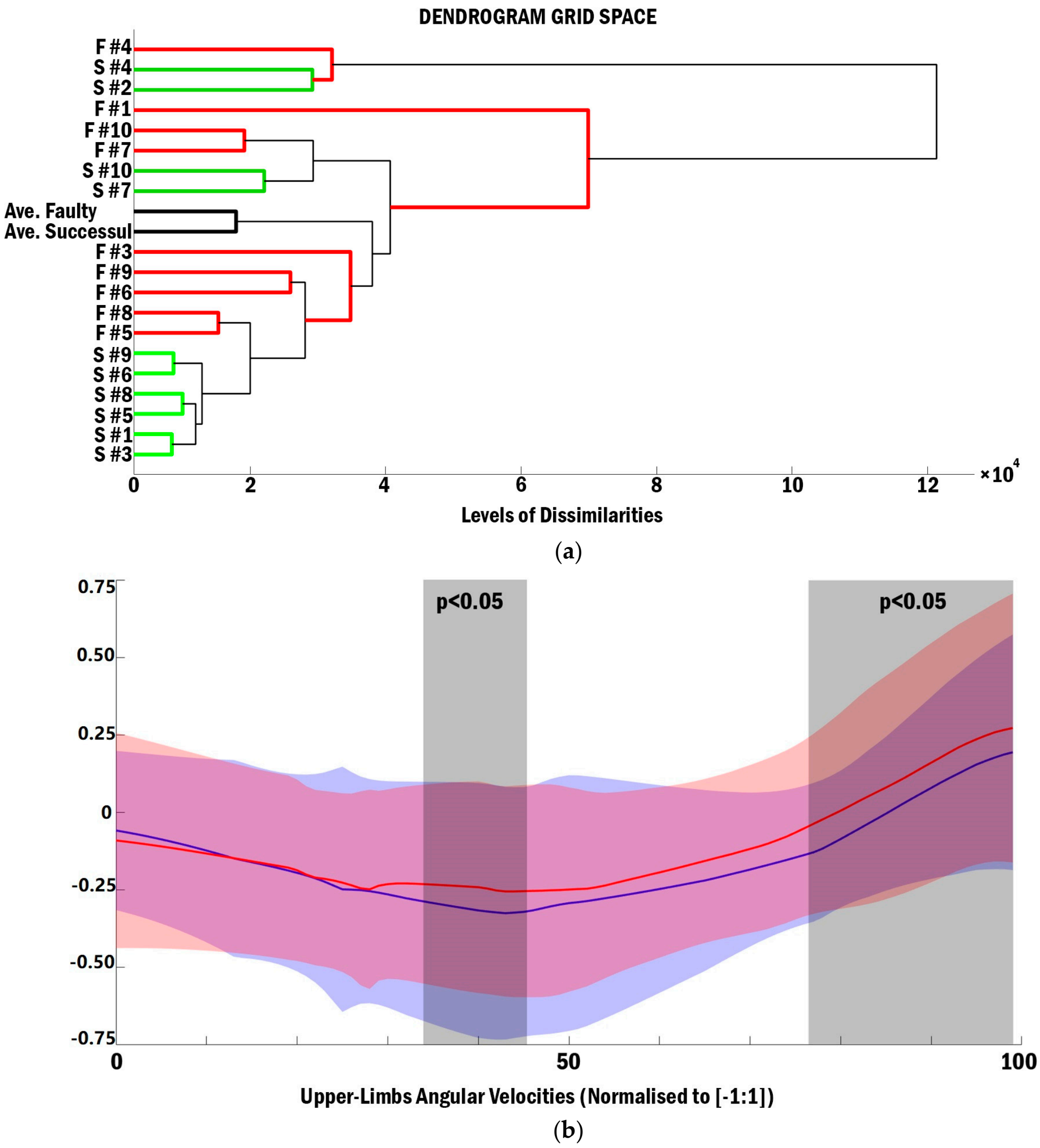

Figure 4. (**a**) Cluster analysis of the upper limb joint angular velocities in successful (green lines) and faulty (red lines) spikes, and (**b**) the SPM analysis portrays significant differences between the upper limb angular velocities in successful (red line) and faulty spikes (blue line) from 35% to 45% and from 76% to 100% of the spike movement (dark grey boxes).

4. Discussion

The aim of this research was to analyse the whole body coordination pattern differences between successful and faulty spikes in young elite volleyball attackers using SOM-based cluster analysis. The major finding of this study was that the upper limb angular velocities (using SOM and cluster-based analysis) were the main contributor to successful spikes among the attackers. The outcomes also showed that no inter-individual specific pattern exists when assessing whole body, lower and upper limb coordination patterning of successful and faulty spikes. Therefore, considerations on the level of analysis are important and likely related to the skill being assessed. It was also demonstrated that the upper limb angular velocities, using SOM and cluster-based analysis, were the main identifier between successful and faulty spiker coordination patterning among the attackers.

Adaptable movement in human performances is facilitated by the redundant degrees of freedoms (DOF) [22]. The CNS consistently constrains and modifies these DOFs using external (environmental) constraints and current spatiotemporal circumstances of the segment to find an optimal solution to the task [23]. The more skilled an individual becomes, the greater the integration of kinematic elements to aid in a coordinated, smooth performance by unifying the DOFs [24]. This increment in DOFs results in an individually unique movement pattern within athletes. The primary, and most important, observation of this study was that the whole body coordination patterning (joint ROM and angular velocities of whole body and centre of mass spatiotemporal characteristics) for each individual is unique. The cluster analysis also confirmed that regardless of success or error in the final result, the whole body pattern remains similar for each attacker. These observations reinforce the notion that the CNS increases the automaticity of the movement by limiting the DOFs to optimise the movement into a stable coordination pattern, allowing the working memory to be free to efficiently respond to further environmental disturbances [25]. The success or error of skill outcome, therefore, is linked to more fine elements of skill execution.

Similar to whole-body SOM and cluster analyses, a unique upper and lower limb coordination patterning was shown across all attackers, except the lower limb coordination patterning of participant 7 and upper limb coordination patterning of participant 3. Specific details in the average whole body coordination patterning reveals one large difference (the black trajectory on the top-right of the SOMs in Figures 2 and 3) and several small differences (approximately the final 25% of the movement) between the successful and faulty spikes patterns. Previous kinematic data has demonstrated that joint angular velocity for the orientation leg, knee, hip, and also trunk were significantly larger in successful spike trials [1]. Higher Euclidean distances between successful and faulty spikes (since the green ridges have more neighbouring distances than blue ridges) also confirm the differences between the successful and faulty coordination patterns. To this end, it could be claimed that although the CNS increases the movement efficiency through controlling the DOFs, the angular velocities may be the main contributors to the success rates of the volleyball attackers.

In the ROM analysis in our paper, the SOMs and BMU trajectories portrayed almost identical patterns in whole body and lower limbs; however, there was a visible difference between the upper limb ROM patterns in successful and faulty spikes. Further cluster and SPM analyses confirmed no significant differences between the ROM patterns of the whole body joint ROM in both successful and faulty spikes. It could be postulated, therefore, that skilled athletes model a complete linkage of the desired spike movement with defined DOFs and that the working memory automatically runs this model as a whole.

Interestingly, the SOM analysis demonstrated considerable differences across the individual angular velocities of the upper limb joints. Nevertheless, the mean angular velocity patterns were similar in the whole body and lower limb data (black lines). Conducting the cluster analysis, it was observed that the upper limb angular velocities were similar between the successful and faulty spikes of most of the attackers. In the left-handed attackers (participant 2 and 4, yellow and red lines in Figures 1–3, respectively), the upper limb angular velocities of successful trials were more similar to each other. Among participants 1, 3, and 5–10, who were right-handed attackers, the upper limb angular velocities of successful/faulty trials were more similar (Figure 4b). The SPM analysis, in line with these findings, demonstrated significant differences between the upper limb angular velocities of the successful and faulty spikes around take-off (35–45% of the spike performance) and the last 25% of the movement (from where the attackers accelerate their hands to hit the ball).

Kinematic results demonstrate that trunk and arm swing velocities at the take-off moment and the wrist angular velocities at impact were significantly higher in successful spikes [1].

Generally, in volleyball the main objective of an attacker is to achieve the greatest possible height to benefit from a larger field size for ball placement [4,26]. Therefore, a plethora of research focuses on increasing jump height through assessing lower limb explosive strength or coordination. The results of this study, in contrast, emphasise that the lower limb total coordination patterning might not be the primary element dictating the success rate of the volleyball spike, but rather the upper limb angular velocities. To this end, the majority of volleyball players and trainers place a premium on lower limb strength and capabilities during the volleyball spike, therefore, attackers have excellent lower limb capacities, but the upper limb capacities can be relatively untrained and thus lead to imbalances during skill execution. The result could either be faulty attacking performance or, more long-term, the potential for overuse injuries. Therefore, it is recommended that training focus on upper limb performance to improve volleyball spike performance.

Limitations

Since the SOM analysis assesses global coordination patterns, ROM, and angular velocities, this level of analysis is not capable of presenting specific joint differences between successful and faulty spike performance. Nevertheless, the primary aim of this study was to analyse the attackers' performance on a global level, therefore the results of this study provide a unique contribution.

5. Conclusions

The SOMs-based cluster analysis, as a class of artificial neural networks, was shown to be an appropriate tool for analysing and identifying whole body coordination pattern differences between successful and faulty spikes in elite volleyball attackers. Findings indicated that regardless of success or error in the outcome of a volleyball spike, whole body coordination patterning is unique for each participant. The CNS strictly governs the entire body and joint ROM to control redundancy of the DOF and maintain coordination. Analysis of the upper limb angular velocity demonstrates differences between successful and faulty spikes within the individual attackers. To this end, despite previous research identifying that the lower limbs are the main contributor to successful spike performance, the upper limbs seemingly play a pivotal role in the success rate of the volleyball spike. To this end, it is recommended that volleyball coaches design their training programs to focus on the upper extremities, and also to focus on limbs as a whole rather than individual segments. The SOM analysis was also shown to be a useful tool for the evaluation of several segments on a global level and provides practitioners with useful complex skill execution measures.

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Whole body coordination patterning in volleyball spikes under various task constraints: exploratory cluster analysis based on self-organising maps

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ABSTRACT

Task and environment-related constraints can influence spike performance in volleyball players. This study was designated to investigate the impact of awareness of the presence or absence of a defensive block by the opponents on the performance and coordination pattern of spikes in elite volleyball attackers. Simulating a real-game scenario, 10 elite youth attackers (aged 15.5 ± 0.7 years) executed six spikes each with prior notification about the presence/absence of defences and six spikes without any notification. In each condition, they were blocked by two opponents in three trials. The coordination patterning of the attackers was explored using cluster analysis based on a Self-Organising Map (SOM). The SOMs and the cluster analysis showed that the coordination pattern of the spike execution was very individual-specific; however, in the third layer of the cluster analysis, it was revealed that the movement pattern of spike execution had similarities in the scenario wherein the players had prior awareness of the defences. Providing the attackers with information on the opponents' condition or performance could shift the attackers' focus from a game-oriented condition to the rivals' behaviour, which consequently resulted in deterioration of their spike performance.

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Introduction

In volleyball, the spike performances are crucial for winning in volleyball competitions (Fuchs et al., 2019). To perform an effective spike, a highly coordinated pattern of total body muscular activities is necessary (Serrien et al., 2018). By adopting a synchronised and harmonised inter-segmental movement from the lower to the upper extremities, the attackers are required to detect the spatiotemporal pattern of the ball trajectory and position of the defence precisely, and spike the ball at the best possible moment (Sarvestan et al., 2018, 2019; Serrien et al., 2018). Nevertheless, even a small deficit in

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any aspect of the 'motor program' could affect the whole body movement chain and consequently influence the entire movement and thereby, the performance.

Principally, the motor control system continually tries to maintain the whole body coordination patterning and adopts controlling strategies for counterbalancing any internal and external perturbations (Shafizadeh et al., 2018). Synergetic kinematic patterning of individual joints or segments is claimed to be governed by integrated cyclic sources of information from both the environment and the central nervous system (Wilson et al., 2005). Although the neuro-musculoskeletal system adapts high numbers of degrees of freedom to deal with internal and external perturbations, several intrinsic and extrinsic elements, including task and environment constraints or neuro-musculoskeletal status, could impact the coordination patterning among individuals (Latash, 2012; Shafizadeh et al., 2018). In this regard, based on the concept of dynamic system theory, each motor performance is self-organised by the interactions of all the existing constraints (Diedrich & Warren, 1995; Stergiou & Decker, 2011). From the cognitive load perspective, the limited capacity of the working memory may restrict an athlete from optimal motion patterns during a game with highly dynamic task and environmental-related constraints (De Jong, 2010; Runswick et al., 2018). Furthermore, the accumulation of several constraints, such as game-related stresses, monitoring opponents' behaviours, or coach's comments on the performance and actions that need to be executed, could highly preoccupy this capacity and result in a dysfunction (Runswick et al., 2018). In volleyball competitions, every attacker performs more than 20 spikes per game (on average) under several constraints. These constraints could be task constraints (such as predicting different ball trajectories to hit) and environmental constraints (such as the number of opponents and the teams' scores). Each of these constraints might affect the patterning of movement coordination.

Self-Organising Maps (SOMs), which is a class of artificial neural networks, has been, lately employed to explore human movement in a disparate dimension (Serrien et al., 2017). SOMs have been successful in identifying complex patterns in various multi-dimensional sports movements and the effects of several constraints thereon. For instance, it was demonstrated that SOMs could identify the changing coordination profiles in golf putting with increasing target distances (Lamb et al., 2011). Some other studies investigated the effects of speed on whole-body coordination in cross-country skiing and volleyball (Lamb et al., 2014). More recently, SOMs have been employed to study intra-seasonal variability in team-handball throwing patterns (Serrien et al., 2016). SOMs can map the multi-dimensional kinematic time series representing the whole-body coordination on a two-dimensional (2D) grid, thus reducing it to a 2D coordinate trajectory (Serrien et al., 2017). This mapping is performed in such a way that the original topology in the dataset remains maximally preserved, i.e., patterns that are similar to one another in the original higher-dimensional kinematic space are mapped close to one another in the 2D SOM space.

Given that the coordination pattern of a volleyball spike (at any level of analysis) consists of a set of non-linear variables, employing a multivariate analysis appears suitable for the interpretation of the coordination patterning of the attackers. In the present study, we employed a cluster analysis of multivariate coordination profiles to gauge (dis)similarities at the levels of individual-to-individual variabilities and induced variabilities owing to the task constraints. The benefit of hierarchical cluster analysis is that the hierarchical tree could precisely detect and demonstrate the levels of (dis)similarity as a nested sequence or dendrogram (D'Andrade, 1978; Chatfield, 2018). Data reduction, group-based prediction, data exploration, and hypothesis generation type of studies are primarily proposed to employ cluster analysis (Chatfield, 2018; Everitt, 2005; Rein et al., 2010). Human movement patterning, from simple tasks, such as walking and reaching, to more complex tasks in sports such as handball, swimming, volleyball, and soccer, was already investigated using cluster analysis (d'Avella et al., 2006; Rein et al., 2010; Schorer et al., 2007; Toro et al., 2007). As an instance, the displacement data of the hip, shoulder, elbow, and wrist joints in a handball throw was dimensionally redacted using cluster analysis (Schorer et al., 2007). Generally, this type of analysis could be used to study clustering at various levels, so that we can see if the coordination patterning is primarily clustered according to the experimental manipulations or the individual characteristics (Rein et al., 2010).

Based on the literature discussed above, the impacts of task constraints on the coordination patterning of volleyball spike performance among elite players has not been formerly investigated. Analysis of volleyball spike coordination patterning under different task constraints could beneficially feed the volleyball coaches and players about how, when and to what extent these constraints could impact their spike performances. To this end, this study was aimed at a SOM-based exploratory cluster analysis on whole-body coordination patterning of volleyball spikes with and without awareness of the constraints among a group of young elite volleyball players. It was hypothesised that having prior information regarding the presence or absence of the blocks (as a constraint) could significantly affect the coordination patterning of the spike performance.

Methods

Participants

Of the 13 elite young male volleyball players who participated in this study, the data of 3 participants were excluded owing to issues related to recording. Table 1 presents the characteristics of the included participants. The selected participants consisted of opposite (opposing side) spikers, wing spikers, and middle blockers and included eight right-handed and two left-handed players. Furthermore, the participants played at the national level. No musculoskeletal injuries, including muscle, tendon, and ligament torsion, bone fracture, and joint laxation within the last one year was reported, and the players were healthy at the measurement venue. The purpose of the study and the procedure were explained to the participants, and written informed consents were also signed by their parents and coaches.

Table 1. Characteristics of included participants.

Participant	Age (year)	Height (cm)	Weight (Kg)	Experience (year)	Game Position
#1	16	191	74.9	7	Wing Spiker
#2	16	188	69.2	6	Wing Spiker
#3	16	199	77.8	8	Wing Spiker
#4	15	186	75.4	6	Opposite Spiker
#5	15	191	75.1	7	Middle Blocker
#6	16	195	84.5	7	Wing Spiker
#7	16	193	77.6	6	Wing Spiker
#8	16	195	84.1	8	Middle Blocker
#9	16	198	77.3	7	Middle Blocker
#10	15	193	71.8	7	Wing Spiker
Mean±SD	15.5 ± 0.7	192.9 ± 4.1	76.9 ± 4.7	6.9 ± 0.7	-

Procedures

After a 15 min combined cardiovascular and volleyball-specific warm-up under the supervision of the researchers, the athletes were acquainted with the procedure. Each player performed six familiarisation spike trials (three times with the blockers being present, and three times without). Next, the participants executed 12 spikes under 2 different constraints; the first constraint included six spikes with prior notice by the examiner as to whether the athlete would be blocked or not (Aware = A), and six spikes without prior notice by the examiner (Non-Aware = NA). The entire spike performances were executed in a random order, in which the attackers performed all 12 spikes randomly without prior information about the next spike condition. Rest intervals (30s) were allowed between two consecutive trials for the players to prevent fatigue. During both A and NA conditions, the second constraint was applied when two defences tried to block (B) the attackers three times out of the six spikes at the command of the examiner, and the other three times, the blockers only pretended that they were ready to block (Not-Block = NB). When the player was informed of the presence of the blockers, the examiner would make the following announcement: 'You are going to be blocked by the opponents. Try your best to score a point'.

Earlier studies on this subject fixed the location of the impact of the ball to maintain identical conditions for all the participants (Wagner et al., 2009); however, this decreases the ecological validity of the results because such an isolated testing condition could impact the observed motion patterns in real-game conditions. To this effect, a setter was employed throughout the experiment to set the ball for the attackers. The skills and capability of the setter were approved by the coaches; only two errors were recorded in 120 settings and these were excluded from further analysis. The setting errors included those settings that the ball slipped from the setter's hands, and the set ball altitude was so high or too low to spike, as judged by an expert coach. The impact location consistency in three-dimensions was calculated in terms of a range in the impact location. Similar to the spikers, the setter was also aware/not aware of the blocking conditions. The spikes were executed from an individually-chosen starting point and were oriented towards the tossed-up ball.

Marker placement, data recording, and processing

A total of 37 passive reflective markers (diameter 14 mm) were attached to anatomical landmarks, including the head (2 markers on the frontal lobe and 2 markers on parietal lobe bones), C7, right scapula, T10, clavicle, sternum, left and right acromions, upper arms, elbows, forearms, medial and lateral epicondyles of humerus, anterior superior iliac, posterior superior iliac, thighs, knees, tibias, ankles, toes and heels, by an experienced researcher in order to establish the local coordinates systems of the segments (Kainz et al., 2017; Rahmatalla et al., 2008; Sarvestan et al., 2020; Shiratori et al., 2011). Placement of the entire markers was marked on the skin in order to find the exact location of marker placement in case of detachment, and the calibrated markers were used as tracking markers during the performances. The spatial-temporal trajectories in three dimensions were recorded for further analysis by employing six Vicon® VCAM motion capture cameras (Oxford Metrics, Oxford, UK) at a sampling frequency of 180 Hz (Sarvestan & Svoboda, 2019). The reconstruction and labelling were carried out using Vicon® Nexus software (Version 1.8.6, Oxford Metrics, Oxford, UK). The spline and pattern methods were applied to perform the gap-filling process for the missed markers (no longer than 10 frames), and a fourth-order Butterworth filter (zero-lag) at a cut-off frequency of 10 Hz was used to remove the noise and smooth the marker trajectory (Skogstad et al., 2013). A global reference frame was defined with the positive Y-axis in the direction of the spike, the positive X-axis in the right direction, and the positive Z-axis in the upward direction.

A 'Plug-In Gait' full-body model was employed to calculate all the variables presented in Table 2, which were used in the coordination analysis. In this model, the joint centres and angles and the segment angles were defined from the marker set of the static trial (the reference frame) prior to the test (the moving frames) (Kainz et al., 2017). The segment and total body centre of mass were calculated similar as Ploof et al. (2017). During the dynamic trials, the output angles for the entire joints were computed from the 3 dimensional Cardan angles derived by comparing the relative orientations of the two segments, with the abduction/adduction, flexion/extension and external/internal rotation order among two adjacent segments (Kainz et al., 2017). The progression angles of the feet, pelvis, thorax and head were also the YXZ Cardan calculated from the rotation transformation of the participant's progression frame for the trial onto each segment orientation. In addition to the variables shown in Table 2, the corresponding velocities were also calculated (using the central difference method). It has resulted in a total of 64 kinematic variables being used to define total-body coordination profiles.

Table 2. Overview of kinematic variables used in the coordination profile analysis.

JOINT/SEGMENTS	ABBREVIATIONS	DESCRIPTION
centre-of-mass	CoM_X, CoM_Y, CoM_Z	3D coordinates of the total-body centre of mass
Left and right lower limb joints	$Lhip_X$, $Lknee_X$, $Lankle_X$ $Rhip_X$, $Rknee_X$, $Rankle_X$	Flexion-extension angles of the hip, knee and ankle joints.
Left and right upper limb joints	$Lshoulder_X$, $Lshoulder_Y$, $Lshoulder_Z$, $Lelbow_X$ $Rshoulder_X$, $Rshoulder_Y$, $Rshoulder_Z$, $Relbow_X$	Shoulder ab/adduction, horizontal ab/adduction and internal/external rotation, elbow flexion-extension
Trunk	$Pelvis_X$, $Pelvis_Y$, $Pelvis_Z$ $Spine_X$, $Spine_Y$, $Spine_Z$ $Thorax_X$, $Thorax_Y$, $Thorax_Z$	Pelvis tilt, obliquity, and rotation (absolute) Spine flexion/extension, lateral flexion, and rotation (relative) Thorax tilt, obliquity, and rotation (absolute)
Neck and head	$Neck_X$, $Neck_Y$, $Neck_Z$ $Head_X$, $Head_Y$, $Head_Z$	Neck flexion/extension, lateral flexion, and rotation (relative) Head tilt, obliquity, and rotation (absolute)

Data pre-processing

Prior to carrying out further analysis, the data files of each spiking movement were trimmed between the start of the plant phase and the point of ball impact and linearly interpolated to 101 data points (0%–100%). The beginning of the plant phase was defined as the instant of both feet ground contact, and the impact moment was defined as that when the acceleration measures of the spiking hand abruptly decreased in the Y-direction (Wagner et al., 2014). Data sets of the left- and right-handed participants were arranged in such a way that the dominant side was consistent among them. The averages of the three spikes per condition for each player was used for further analyses. For participant 3, the data were missing in the NB-NA condition.

Coordination profiling with self-organising map analysis

A Self-Organising Map (SOM) analysis was used to construct the whole-body coordination profiles of each spike motion (Kohonen, 2001). Basically, a SOM is a 2D grid of units with a weight-vector associated with each unit. These weight vectors (w) are meant to be prototype patterns of the input vectors (v). In the present study, the input vectors are the coordination states (collection of kinematic variables) at each time point:

$$vi(t) = [\psi i, 1(t) \ldots \psi i, 32(t)\ \varphi i, 1(t) \ldots \varphi i, 32(t)]t \quad (1)$$

where ψk and φk represent the degrees-of-freedom and the corresponding velocities (k = 1, . . ., 32; see Table 2). The index i represents the mean of all the trials (i = 1, . . ., 39); The number of trials, i.e., 39 was arrived at considering that there are four trials per participant minus missing trial data for participant 3 for one condition. The time index t runs from 0 to 100 (normalised spike movement duration). Before feeding the data to the SOM algorithm, all the input vectors were normalised component-wise with range scaling to a [−1; 1] interval. This step was necessary because of the large differences of the natural scales, on which the original kinematic variables were present. By iterative updating of the weight vectors using both competition and cooperation among themselves, they converge to a stable solution through a self-organising process (Kohonen, 2001). This training process, which adopted the *Normal* (default) map size, *Gaussian* neighbourhood, *Hexagonal* lattice and *Sequential* training type, resulted in a grid of units that were arranged in such a way that the neighbouring units represented closely similar coordination states. In the final SOM, the unit with weight vector that had the smallest Euclidean distance to the input vector was termed the best-matching unit (BMU) for that input vector. In this way, the multi-dimensional kinematic time series were represented by a 2D BMU-trajectory and the SOM was able to map topologically similar patterns at similar locations of the map. The next step involved constructing a pair-wise distance matrix between all the mean coordination patterns, using the trained SOM as follows:

$$D_{i,j} = \sum_{t=0}^{100} \left[BMU_i(t) - BMU_j(t)\right]^2,\ i,\ j\ =\ 1\ \ldots\ 39 \quad (2)$$

.
This distance matrix was then used in the next step for cluster analysis.

Cluster analysis

To examine the inter-individual coordination styles and the effects of task constraints (blocked vs. not blocked and aware vs. not aware), a cluster analysis was performed on the SOM-based distance matrix. 'Hierarchical agglomerative clustering' was performed using the average linkage algorithm. A dendrogram was constructed for visual interpretation of the clustering of the mean trials for each participant and condition. All the data analyses were performed using MATLAB software (v. 2018b, MathWorks, Inc., Natick, MA, USA). The SOM Toolbox for Matlab was used for the coordination profiling step (Vesanto et al., 2000).

Results

The impact location consistency was represented by a maximum distance of 42 cm (mean: 38 ± 4) in the Y-direction, 33 cm (mean: 31 ± 2) in the X-direction, and 29 cm (mean: 24 ± 5) in the Z direction for all the players. Since the attackers had different anthropometrical characteristics, such differences seem logical. Due to which, the within participants' impact location consistency calculations showed the maximum difference of 16 cm (mean: 14 ± 2) in the Y-direction, 10 cm (mean: 7 ± 3) in the X-direction, and 7 cm (mean: 6 ± 1) in the Z direction. Figure 1 shows the trained SOM with the BMU trajectories. Each panel represents the same SOM with individual patterning of all the participants. The SOM is visualised as a unified distance matrix (U-matrix). The cells in the U-matrix represent the distance between the neighbouring SOM units; the colours of the SOM units themselves represent the average distance to all their neighbours. Different areas of the closely neighbouring units (blue areas) could be identified, separated by yellow ridges. The first insight that the BMU trajectories reveal is that the individual players had similar BMU patterning in all the four conditions and no obvious differences could be observed among the task conditions. One exception is participant 1, who had one trial (NB-NA condition) that presented itself as a different coordination pattern compared to his other trials (much shorter BMU trajectory). Particularly noticeable is the BMU patterning of participants 2 and 4, which are located inside the brightest ridges, indicating large distances between their coordination patterns and those of the other participants. Differences between the coordination patterns among the other participants are less pronounced as indicated by the smaller ridges.

Figure 2 presents the dendrogram of the SOM-based cluster analysis. The visual interpretations of the BMU patterns are largely confirmed by the dendrogram. The coordination patterning of participant 4 was very different from those of the other participants. This scenario is repeated for participant 2 at the next level. Besides, this cluster analysis demonstrated a very substantial point about the coordination patterning of individual participant: regardless of their awareness and block conditions, the movement pattern of each player was uniquely individual. As portrayed, except for one trial of participant 1, the entire task conditions were clustered based on the players' individual coordination patterns.

A further observation on the individual motion pattern shows that the coordination patterning of individual players was mostly affected by the awareness of the impending blocking. The coordination patterns of participants 4, 6, 7, 8, 9, and 10 were clustered at the lowest level (third level of clustering) based on their awareness of the blocking. A similar observation holds for participant 1, except in his NB-NA condition. For participants 2 and 3, the presence of defences was the main indicator of movement coordination differences. For participant 5, no task condition resulted in coordination

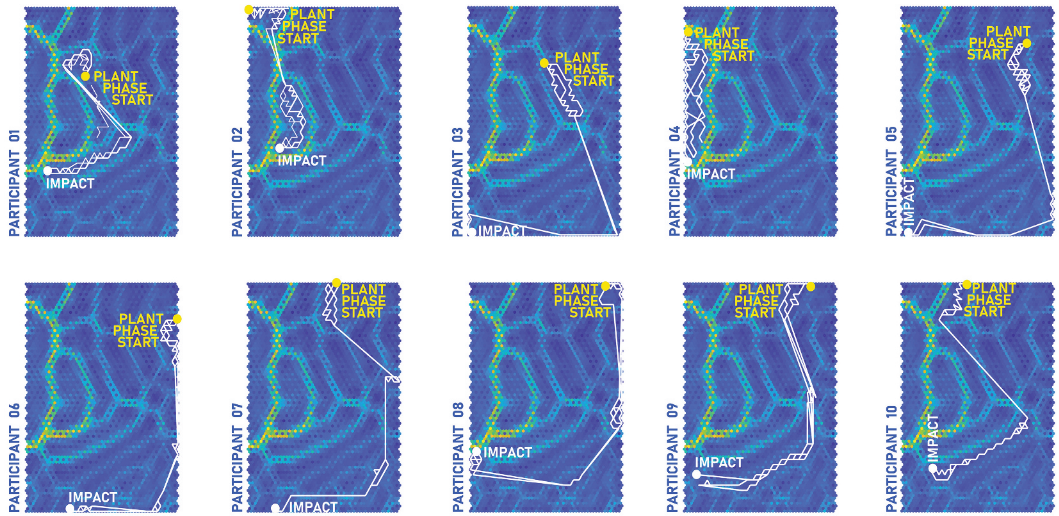

Figure 1. Individual coordination patterning demonstration in SOM: U-matrices with the BMU trajectories (white lines) for the average of each condition among the young elite players. The Euclidean distance is illustrated by colour code, with the blue colour implying a small distance and the yellow colour implying a large distance.

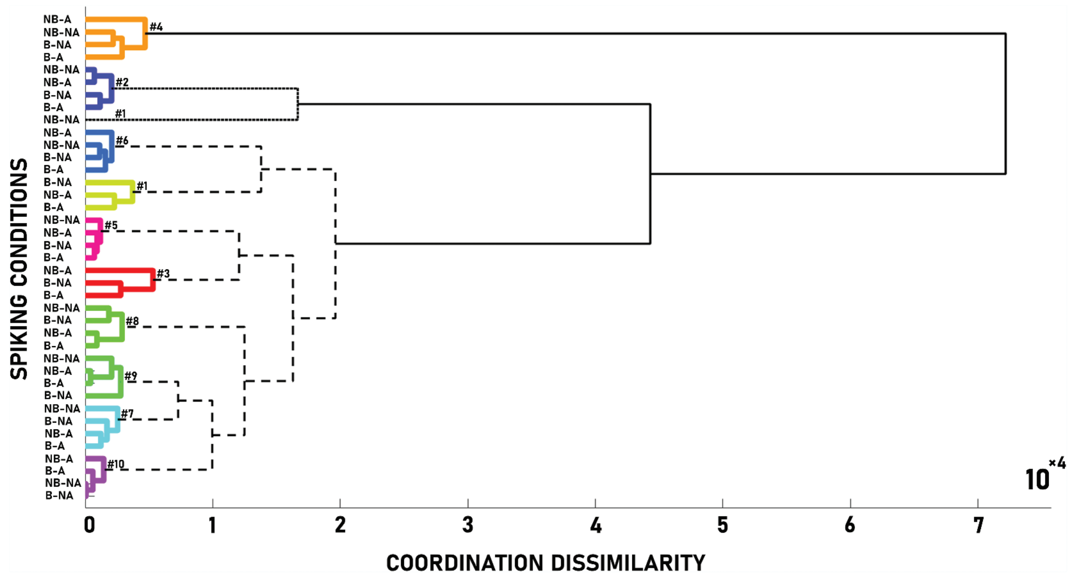

Figure 2. Cluster analysis of spike coordination. NB-NA: Not-Blocked/Not-Aware, NB-A: Not-Blocked/Aware, B-NA: Blocked/Not-Aware, B-A: Blocked/Aware. Each label on the left-hand side presents one mean trial per participant per condition. The horizontal axis indicates the degree of dissimilarity in coordination patterns (in the SOM space; arbitrary units). The colours indicate the identified clusters at the lowest level, which coincide mainly with the participants' ID (only one trial from #1 was not correctly clustered with his other trials). Dashed lines illustrate the clustering of participants 6, 1, 5, 3, 8, 9, 7, and 10. Dotted lines cluster the trials of participant 2 with one trial of participant 1. The highest level of clustering (greatest coordination dissimilarity) is between participant 4 and the rest of the participants.

pattern clustering, and all his trials were very similar to one another, as can be seen from the low value of dissimilarity at which they are clustered.

Discussion and implication

In this study, we explored the whole-body coordination patterning in volleyball spikes under different task constraints among young elite volleyball players, using SOM-based cluster analyses. The main finding of this study was that neither the awareness constraint nor the blocking constraint could differentiate between inter-individual coordination patterning; instead, each player had his own unique movement pattern. In the third level of cluster exploration among individual players, it was revealed that the coordination patterning of spike performance was mostly identical under similar awareness constraints, which meant that prior information about the future circumstances had more impact on the coordination patterning differentiation of the spike performance in comparison with the presence or absence of defences.

Prior to any interpretation on the outcomes, it should be understood that participants 2 and 4 were left-handed. For this reason, the differences in the BMU trajectory patterning and the cluster analysis seemed to be logical between these two participants and the rest.

A number of earlier studies, which were conducted from different theoretical perspectives of movement patterning, mostly observed that an increase in the skill acquisition was related to a decrease in the coordination variability (Button et al., 2003; Fleisig et al., 2009; Stergiou & Decker, 2011; Travassos et al., 2013; Wagner et al., 2012; Whiteside et al., 2015). The SOMs in the current study revealed that the entire coordination patterning of volleyball spikes among young elite attackers followed a similar pattern under all constraints, which was in line with previously conducted researches (Stergiou & Decker, 2011; Wagner et al., 2012; Whiteside et al., 2015). As Figure 1 showed, except participant 4, the movement patterning of spike performance directed in a mostly similar path from the plant phase inauguration to the impact moment. Clearly, it can be claimed that such consistency and regulated movement pattering among young elite volleyball players are associated with an autonomous stage of cognitive processing, which follows the ecological dynamics for decision making. To support this claim, the duration of spike performance must be considered, in which the attacker has less than two seconds to move towards the ball, predict the ball trajectory, jump, observe the defending conditions, and spike the ball at the best possible moment. To this effect, the attackers seem to be obliged to minimise the impact of the constraints on the working memory by recruiting unified self-organised coordinative structures from their autonomous nervous system. Employing this approach, the central nervous system (CNS) maintains the movement stability, which is attributed to an accurate motor function (Travassos et al., 2013). From the ecological point of view, the CNS maintains the coordination patterning to a low-dimension stable motor programme to save it from any perturbation and increase the chance of success. Here, another issue arises—to what extent does the autonomous system provide the attackers with unified coordinative structures? In which part of the movement patterning, are these recruited structures identical? To this end, from a closer detailed look at the coordination variability patterns, it could be seen that some diversities of movement patterning placed at the starting and finishing point of the movement were present. There were mostly identical patterns in the middle of the spike performance among attackers 1, 2, 3, 5, 6, 7, 8, and 10, which approximately started by the take-off phase and ended with the horizontal abduction of the upper arm of the spiking hand in all the four task constraints. This shows that almost similar coordinated structures were employed by attackers in this part of spike movement. Although the coordination patterning lines of attacker 9 were not fully overlapped, mostly similar patterning was also observed from the take-off to the upper arm horizontal abduction. Overall, the starting and final phases of spike movement have shown more dissimilarity in the movement patterning, which could indicate that different unified coordinated structures might be responsible for this phase. These observations also support the hypothesis that coordination variability increases at the acceleration phase of the throw in highly skilled basketball players (Button et al., 2003; Wagner et al., 2012); however, it should be noted that the basketball throw is a highly isolated movement compared with volleyball spike. Furthermore, even though the movement patterning of individuals is unique in a specific task, it has been shown that elite athletes adopt flexible tactical approaches apportioned to the environmental shifting (Travassos et al., 2013; Warren, 2006).

Furthermore, not only at the end of the spiking phase but also at the starting phase of the movement (from the plant phase start to the take-off), more diversities were observed in the coordination patterning of all the attackers, except attacker 4. During this phase, the attackers' performance was only constrained by awareness, while from the horizontal abduction to the impact moment, the presence/absence of the blocks could influence their working memory during the running of the motor program. More interestingly, the cluster analyses showed that the movement patterning of attackers 1, 4, 6, 7, 8, 9, and 10 were similar based on their awareness regarding the presence/absence of the defences. This illustrates that the effect of the awareness constraints on the spike performance coordination patterning (especially in the plant phase) was more significant than the blocking presence/absence (among the attackers 2, 3, and 5). Accordingly, it must be taken into account that any extra information regarding the rivals' condition or performance might affect the athletic performance, regardless of the game condition.

In addition to the assumption brought up above, two biomechanical hypotheses also exist. First, given the variability of the tossed ball spatial location (ΔY = 42 cm, ΔX = 33 cm, and ΔZ = 29 cm for all attackers and ΔY = 16 cm ΔX = 10 cm ΔZ = 7 cm for individuals), the attackers had to uniquely reconstruct the unified degrees of freedom (DOFs) for a particular ball position, which increased the bandwidth of the existing coordinated structure at each moment of the spike (Button et al., 2003). Nevertheless, the coordination patterning illustrates that these diversities were not large enough to differentiate the movement pattern in each condition completely. Such slight differences in the coordination patterning at the acceleration phase of the spike could also reveal that the acceleration phase of the spike performance was governed by the autonomous nervous system, while some unified DOFs existed in the autonomous system as possible alternative options to be immediately employed under different task constraints. The second hypothesis, which overlaps with the two previous assumptions, mainly focuses on the joint-space data (Kudo et al., 2000; McDonald et al., 1989). As a result of the change in the key parameters of the spike in the acceleration phase, which could be associated with either the presence of defences or the tossed ball position, the joint-space adaptation of individual joints compensates for any changes in the movement of the previous joints to stabilise the functional level at the impact moment. In line with mentioned hypothesis, Figure 1 demonstrates that, except attackers 4 and 9, the impact moment of the attackers was placed at the same position in the coordination patterning of their spike performance. This supports the assumption that the spatiotemporal position of each joint is based on self-organisation of the effective DOFs in order to execute the desired action as efficiently as possible.

The higher level of cluster analysis (outer layer), besides, demonstrated that, except NB-NA condition of attacker 1, the movement patterning of each participant was similar in all conditions. This outcome confirms that although the awareness of future condition might influence the athletic performance, every player has his own unique coordination patterning and no universal coordination patterning exists for spiking performance. Therefore, the concept of 'One-size-fits-all' training program, which is generally adopted by the volleyball coaches and trainers to train their athletes, regardless of their individual abilities and motor learning capacities, should undergo changes (Minett & Costello, 2015). Regardless of the game position (e.g., wing spiker, middle spiker, or opposite spiker), these findings reveal that even players with similar game position would not necessarily follow the same coordination patterning in their spike performance (e.g., participants 1, 5, 9, and 10 were wing spikers). Accordingly, employing an identical training program for all the athletes, particularly in elite or highly skilled levels, does not seem to be the best option for enhancing their performance.

Limitations

During the measurement procedure, we instructed the defences to pretend to counter when they were asked not to block. Nevertheless, our observation showed that some defences have not been successful in the 'pretend-to-block' task, which might have affected the coordination pattering of the attackers in some not-blocked condition spikes. Another limitation was that two participants were left-handed; however, the motion capture system was set in a wider area to cover the entire playground.

Further limitation of this study was the participants' population (N = 10), which may impact the statistical power and needed to be fully considered with caution. Nevertheless, only players from the national volleyball team in the U16 category were recruited in this investigation. To this effect, our included sample could be characterised by relatively good homogeneity.

Conclusion

The outcomes of this SOMs-based exploratory cluster analysis support two key principles for coaches during training sessions and game conditions. First, coaches and sport-specific trainers must be aware that movement coordination patterning is exclusively unique to individuals, and even among players with the same game position, with similar tasks in the game, the coordination patterning could be different from one individual to the other. Hence, it is suggested to the volleyball coaches to reorient their sports-specific training programme more towards individual-specific training programs. Second, providing the players with information on the opponents' condition or performance may shift their focus from the game to the rivals' performance, which might affect their autonomy in running spike patterning automatically, and consequently cause deterioration of their performance. Accordingly, any communication with the players must be conducted with caution, so that the athlete's performance does not undergo any deterioration.

Disclosure statement

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3 Discussion

The main objective of this study was to investigate the contribution of biomechanical factors in the accomplishment of successful volleyball spikes among young elite male volleyball players. To address this objective and to accomplish a precise contextualized approach, four studies about the effects of different kinematics and kinetics variables on volleyball spike success rate have been conducted. In the following paragraphs, these studies will be thoroughly discussed. It has been tried to discuss every research study focusing on the main questions linked to the thesis aims.

Study 1: Sarvestan, J., Svoboda, Z., & de Oliveira Claudino, J. G. (2020). Force-time curve variables of countermovement jump as predictors of volleyball spike jump height. *German Journal of Exercise and Sport Research, 50*(4), 470-476.

As it was mentioned in the “Overview of knowledge” section, jump height is one of the main contributors to a better spike performance. To this effect, the first study was conducted to evaluate the contribution of CMJ force-time (F-T) curve factors to verify which could influence spike jump height (SpJH, in which attackers jump to spike during a game-like situation) in young elite volleyball attackers during a simulated game-like situation. Former studies mainly investigated the squat jumps (SJ) and countermovement jumps (CMJ) as the principal tests related to jumping capacities and explosive strength level of volleyball, soccer, basketball and rugby players (Sarvestan et al., 2018; Sarvestan, Cheraghi, et al., 2019; Suchomel et al., 2015). Nevertheless, given that the jumping strategies of the above-mentioned sports are quite different, it seemed generalizing the SJ or CMJ outcomes to sport-specific (i.e., volleyball) jumping capabilities is not accurate.

Despite other studies that highlighted the lower limb strength and power measures as the principal contributors to higher jump altitudes (Rice et al., 2017), our results depicted that the peak and average RFD values had respectively 56% and 58% contribution to SpJHs. Thus, across all F-T curve variables, the peak and average RFD values were the best predictors. These findings suggest that the capacity of the lower limbs' muscles to generate force might have a significant impact in jump height during the game-like condition. These findings supports the findings of McLellan et al. (2011), which found a substantial positive association between RFD and vertical jump height. The attackers effectively triggered and managed the connection between neurological and muscular systems to perform a highly coordinated fast contraction and leap higher, as evidenced by their significant contribution to the prediction of SpJH (Maffiuletti et al., 2016; Wagner et al., 2009). Simply put, the attackers build CoM horizontal velocity in triple-step running in the approaching phase of spike performance, then transfer it to CoM vertical velocity in the plant phase employing the SSC function of ankle plantar flexors, knee and hip joint extensors (Wagner et al., 2009). Achieving such coordinated harmonious muscle activation in a very short period of time is greatly in demand of synchronized muscular activity, which RFD could dependably demonstrate in jumping performance. In practice, and according to the results, it is not the quantity of applied force that assists in jump height, but the force impulse that paves the way for a higher jump height. To that end, it is strongly advised to improve the sports-specific jumping strategy, as well as muscular strength, in order to efficiently activate the optimal muscle function throughout the jump performance. Nonetheless, because the stepping phase of a spike jump differs from that of a CMJ (essentially, the orientation step is in front), it is unclear which leg contributes the most in greater SpJHs (H. Wagner et al., 2009).

On the contrary, other investigations utilizing arm swings found a very poor association between RFD and CMJ height (Lees et al., 2004; Vanezis & Lees, 2005). The key explanation for such a disparity in results appears to be the method of measuring the RFD, since they used isometric muscle contraction (Vanezis & Lees, 2005). In this investigation, we attempted to evaluate RFD during natural muscle performance in CMJ utilizing a force platform, which might be the major source of discrepancy. The performance of CMJ using arm swing is similar to the natural performance of spike jump, in which athletes bent their knees and trunk, and use their arm swing to efficiently recruit the SSC and consequently jump higher (Komi, 2003; Sarvestan et al., 2018; Sarvestan, Riedel, et al., 2019). Several studies attempted to examine the state of isolated lower limb muscles utilizing akimbo-style CMJ (Sarvestan et al., 2018; Sarvestan, Cheraghi, et al., 2019), this upper limb positioning is advised in order to assess neuromuscular condition and achieve the greatest potential performance (Claudino et al., 2017; Claudino et al., 2016;

Claudino et al., 2012). However, employing arm swings shown to boost data reliability because it maintains movement coordination by using hands in a harmonic manner, particularly when the assessment seeks to attain a performance more comparable to the spike movement (i.e., during the game).

The high prediction rate of concentric net impulse in SpJH was one of the study's standout results (37.2 percent). This idea is confirmed by previous research on jump performance among sports science students, which found a rather strong association between net impulse and jump height (Kirby et al., 2011; Mizuguchi et al., 2015). Previous research, on the other hand, reported that neither eccentric nor concentric impulse had a significant link with CMJ height among volleyball players (Dowling & Vamos, 1993; Sarvestan et al., 2018). Such inconsistent results might be attributed to various techniques of calculating jump height. In this work, we used motion capture data to calculate jump height, whereas previous studies used take-off velocity measurements to calculate final leap height, which has been stated to have obvious disparities (Sarvestan et al., 2018; Sarvestan, Cheraghi, et al., 2019). Second, the full positive region of the F-T curve was previously used for impulse computation, whereas parts of this positive area (until the CoM velocity advances to positive values – or the start of the concentric phase) still belongs to the countermovement stretching phase (Dowling & Vamos, 1993). Our work used the same method as Mizuguchi et al. (2015) to properly determine the net impulse in the concentric phase of CMJ. Furthermore, the substantial association between concentric net impulse and SpJH indicates that the area under the concentric component of the F-T curve might be used to predict the jump height status of volleyball spike jump performance.

According to the outcomes, the first hypothesis of this study was partially confirmed, where the impulse, and relative RFD values were shown to contribute to the higher jump heights. Due to which, **Patterning of applying force (impulse) can significantly affect the spike jump heights, not particularly the lower limbs peak strength or peak power.** To this effect, we aimed to investigate how the spike jumping strategy could affect the success rate among the attackers.

Study 2: Sarvestan, J., Svoboda, Z., & Linduška, P. (2020). Kinematic differences between successful and faulty spikes in young volleyball players. *Journal of Sports Sciences*, *38*(20), 2314-2320.

The key element contributing to the CoM horizontal velocity, the orientation step length, has no significant association with the jump height, as previously stated (Fuchs, Fusco, et al., 2019; Ikeda et al., 2018). During the approach phase, no significant changes in step lengths or peak CoM horizontal velocities of successful and erroneous spikes were found. Furthermore, lack of difference in the outcomes might well explain why both successful and faulty spikes having roughly the same approaching phase length. As a result, the attackers' approach technique does not appear to be a predictor of the spike success rate.

The maximal angular velocity of the orientation leg knee joint has been considered as one of the important elements (>80% contribution) in determining the jump height in volleyball (Fuchs, Fusco, et al., 2019). This variable (which is connected to the lower limbs' power and strength and is dependent on coordination ability) is directly related to the lower limbs' muscles' explosive strength (CopiC et al., 2014; Sarvestan et al., 2018). In line with prior investigations, the findings of this study indicated that effective spikes are associated with high angular velocities of the oriented leg knee and hip joints (with considerably large impact size values). Because the same attacker experienced both successful and faulty spikes, it is possible to conclude that the rate of knee and hip extensor muscle activation was greater in successful trials. Although this looked to be the first step of motor impairment, a review of earlier movement frames indicated that hip flexion angles were much higher in the case of successful spikes. Conceptually, we can infer that the players flexed their hip joints more due to the concept of SSC (i.e., the ability of muscle groups to have a rapid concentric contraction immediately after an eccentric contraction) and due to the observed kinematics from hip angles. This movement resulted in a particularly rapid activation of the muscle spindles and duplicated the function of the Golgi tendon (Komi, 2003; Nicol et al., 2006). This strategy might help players generate more trunk momentum, which could result in higher jump heights during the spike. However, this interpretation should be used with caution because we did not employ electromyography and instead relied solely on the kinematics results.

The arm swing-produced momentum is considered to boost jump height during the plant phase (by 10%–28%) and take-off velocity (by 72%), particularly when employed in the harmonic movement of a proximal-to-distal sequence (Chiu et al., 2014; Fuchs, Fusco, et al., 2019; Lees et al., 2004; Sarvestan, Cheraghi, et al., 2019). In theory, an upward acceleration of the upper extremities causes a downward momentum through the CoM, increasing the CoM's vertical impulse (Lees et al., 2004). The participants used this method during the successful spikes: they increased the arm swing velocity to exploit the momentum in their jump heights, which resulted in considerably greater CoM vertical velocities during take-off. It has previously been said that the CoM vertical velocity is the most important component in increasing jump heights (see the use of this variable for the calculation of the jump height) (Pérez-Castilla et al., 2017; Sarvestan et al., 2018). In the case of successful trials, this method resulted in much higher jump and spike heights during the jump phase, followed by significantly longer flying periods. Overall, these techniques allow the player to manage the spike position, the ball trajectory over the opponents' playground, and the greatest potential time to hit the ball (Fuchs, Fusco, et al., 2019; Fuchs, Menzel, et al., 2019; Valadés et al., 2016). Although a couple of variables, such as block failure or ball set, may restrict the attackers' ability to choose the optimal moment to strike the ball, we controlled the block position and impact location for the whole trial to reduce external interferers and solely monitored the attackers' performance independently.

In throwing or hitting sports, the transfer of proximal-to-distal momentum has been discovered to improve arm movement performance (Serrien et al., 2018; Wagner et al., 2014; Wagner, 2011). The activation of the SSC characteristic of the muscle groups is one of the strategy used to optimization of muscular performance in a short period of time (Cormie et al., 2010; Komi, 2003; Sarvestan, Riedel, et al., 2019).

The SSC characteristics of the shoulder horizontal adductors and internal rotators are activated when the shoulder is horizontally abducted; however, there were no significant changes in the maximum angles of shoulder horizontal abduction under both situations during the cocking phase of the jump. These findings show that jump or spike height deficiencies have no effect on arm movement. We found that the tangential velocities of the trunk and elbows were identical under both situations, assuming a same horizontal abduction for the shoulder. Nevertheless, in the event of faulty spikes, the wrist velocity (expressed by the spike velocity at the impact instant) was substantially lower. The drop in wrist velocity might be due to a variety of factors, including reduced jump heights, spike heights, and flight durations. Volleyball players usually make their ultimate decision as soon as possible before the impact moment. We also discovered that effective spikes were executed when players were given a better perspective of the opponents' playground and more flight time: under these conditions, they were able to make the optimal option and execute the spikes in less time and with a broader view over the opponent's court.

Furthermore, we discovered that during successful trials, the players hit the ball somewhat sooner after reaching the greatest CoM altitude: they had more options due to the greater altitude and longer flight duration. Meanwhile, a delay in reaching the maximum CoM height and impact moment, owing to decreased jump and spike heights, resulted in a considerable reduction in spike velocity, resulting in an erroneous spike performance. In fact, a reduced jump height, followed by a drop in spike velocity, limited the options for selecting the optimal alternative; yet, the blocks were able to predict and counter the ball trajectory with ease in this case.

The results of this study revealed that, regardless of the defenders' skill level or attacker's strength, a series of movement deficits, which could be observed in kinematic variables (e.g., lower hip and knee angular velocities during extension, jump and spike heights, and spike velocity), are the primary cause of attackers' poor spike performance. Consequently, independent of the influence of blocks, volleyball players should strive to improve their spike performance coordination, which may be achieved by practicing harmonious spatiotemporal movements of the neuromuscular system under varied real-game simulated conditions. Higher angular velocities of the hip and knee joints, along with effective arm swing use, can boost jump height during spikes performance in a real-game environment, according to this study.

To this effect, the second hypothesis of this study was confirmed, where the take-off velocity, jump heights, spike height and spike velocity values where greater in successful spikes. **Although the orientation-leg knee joint angular velocity could affect the spike jump heights, the role of upper limbs**

(a coordinated movement of the trunk, arms and forearms) in the accomplishment of a successful volleyball spike is significant. Therefore, we aimed to investigate how the coordination patterning is different between successful and faulty spikes among the attackers.

Study 3: Sarvestan, J., Svoboda, Z., Alaei, F., & Mulloy, F. (2021). Analysis of Whole-Body Coordination Patterning in Successful and Faulty Spikes Using Self-Organising Map-Based Cluster Analysis: A Secondary Analysis. *Sensors, 21*(4), 1345.

The redundant degrees of freedom (DOF) permit adaptable movement in human performances (Wang et al., 2013). To discover an appropriate solution to the desired task, the CNS continuously constrains and adjusts these DOFs based on external (environmental) restrictions and the segment's present spatiotemporal conditions (Chang et al., 2020). The stronger an individual's skill level, the more the integration of kinematic parameters to help in coordinated and smooth execution by unifying the DOFs (Schmidt & Lee, 2011). As the number of DOFs increases, athletes develop their own movement pattern. The study's main finding was that each individual's whole-body coordination patterning (joint ROMs and whole-body angular velocities, as well as centre of mass spatiotemporal features) is uniquely different. The cluster analysis also revealed that, regardless of whether the ultimate outcome is successful or incorrect, each attacker's whole-body pattern is consistent. These findings support the theory that the CNS enhances the automaticity of movement by restricting the DOFs in order to optimize the movement into a stable coordination pattern, freeing up working memory to respond to further environmental disturbances (Verrel et al., 2013). As a result, the success or failure of a skill outcome is tied to increasingly fine components of skill performance. A distinct upper- and lower-limb coordination patterning was seen across all attackers, as it was in the whole-body SOM and cluster analyses. Between the successful and erroneous spikes patterns, there was one big difference (the black trajectory on the top-right of the SOMs) and a couple of small variances (roughly the final 25% of the movement) in the average whole-body coordination patterning. Former kinematic data (study 2) portrayed that the orientation leg's knee angular velocities and the hip and trunk velocities were significantly greater in successful performances (Sarvestan, Svoboda, &

Linduška, 2020). Higher Euclidean distances between successful and faulty spikes demonstrate the distinctions between the successful and faulty coordination patterns (since green ridges have higher adjacent distances than blue ridges). Thus, it appears that the upper limb velocities (here mostly angular velocities), in comparison with lower limbs, have more contribution to the success rate of volleyball spike performance.

Outcomes of study 3 also revealed that the interindivudal best matching unit trajectories of the whole-body and lower-limbs ROMs were similar, while the upper-limbs ROMs were considerably different. Further cluster and statistical parametric mapping analysis revealed no considerable difference among the whole-body joint ROM patterns in successful and faulty spikes. It suggests, that talented athletes model a complete linkage of the intended spike movement with defined DOFs in their working memory, and that this model is automatically executed as a whole. Surprisingly, the SOM analysis revealed significant heterogeneity in individual upper-limb angular velocities. Although the mean angular velocity patterns in whole-body and lower-limbs data were almost identical, the cluster analysis showed that the upper limb angular velocities of the successful and erroneous spikes of the majority of the attackers followed a similar pattern. The upper limb angular velocities of successful trials were more comparable in left-handed attackers (as could be seen among participant 2 and 4). Furthermore, the SPM analysis revealed considerable difference in the upper limb angular velocities of successful and faulty spikes around take-off, and the final phase od the spike performance before hitting moment. As study 2 depicted, successful spikes had considerably greater trunk and arm swing velocities during take-off, as well as wrist angular velocities at impact, according to kinematic studies (Sarvestan, Svoboda, & Linduška, 2020).

In volleyball, an attacker's main goal is to reach the highest potential jump heights in order to profit from a wider court size for ball placement (Sarvestan, Svoboda, & de Oliveira Claudino, 2020; Sattler et al., 2015). In this regard, a slew of studies have focused on improving jump height by evaluating lower-limb explosive strength or coordination. The findings of this study, on the other hand, suggest that upper limb angular velocities, not lower limb total coordination patterning, may be the most important factor determining the success rate of the volleyball spike. Consequently, the majority of volleyball players and trainers place a premium on lower-limb strength and capabilities during the volleyball spike, and as a results, most of the attackers have excellent lower-limb capacities, but their upper-limb capacities may be underdeveloped, resulting in skill execution imbalances. The end consequence might be poor offensive performance or, in the long run, the risk of overuse injury. To this end, we highly suggest the trainers and coaches to enhance the lower- to upper-limbs movement fluency so the the te players' technique enhances parallell to their strength capacities.

Hence, the third hypothesis of this study was rejected, where the whole-body coordination patterning was not difference between successful and faulty spikes. To this effect, we can claim that it is the **upper limbs angular velocities play a substantial role in spike success rate.**

Study 4: Sarvestan, J., Svoboda, Z., Baeyens, J.-P., & Serrien, B. (2020). Whole-body coordination patterning in volleyball spikes under various task constraints: exploratory cluster analysis based on self-organising maps. *Sports Biomechanics, 1-15*.

From dynamical system theory, several investigations done from various theoretical viewpoints of movement patterning found that an increase in skill learning was associated with a decrease in coordination variability (Button et al., 2003; Fleisig et al., 2009; Stergiou & Decker, 2011; Travassos et al., 2013; Wagner et al., 2012; Whiteside et al., 2015). According to the SOMs in the fourth study, the complete coordination patterning of volleyball spikes among young elite attackers followed a similar pattern under all limitations, which was consistent with former studies (Stergiou & Decker, 2011; Wagner et al., 2012; Whiteside et al., 2015). For example, the left-handed players had similar coordination patterning than the right-handed players, and every attacker had his unique spike performance. Apparantly, such regularity and controlled movement pattering among young elite volleyball players might be linked to an autonomous stage of cognitive processing that follows ecological dynamics for decision making.

To back up this assertion, we must consider the attacker's spike performance time, which is less than two seconds to move towards the ball, estimate the ball's trajectory, jump, watch the defending circumstances, and spike the ball at the best possible time. As a result, the attackers appear to be obligated to acquire unified self-organized coordinative structures from their autonomous nervous system to reduce the impact of the limits on working memory. The CNS maintains movement stability via this method, which is credited to precise motor function (Travassos et al., 2013). In terms of performance ecology, the CNS keeps coordination patterning to a low-dimension stable motor program to protect it from disruption and maximize the likelihood of success. Another question emerges here: to what degree does the autonomous system supply uniform coordinative structures to the attackers? Are these recruited structures identical in which component of the movement patterning? To this purpose, a closer examination of the coordination variability patterns revealed that there were some differences in movement patterning at the movement's beginning and ending points.

Outcomes of study 4 also portrayed a similar coordination patterning (less variable movements) in the mid-part of the spike performance, which roughly began with the take-off phase and terminated with the horizontal abduction of the spiking hand's upper arm. This demonstrates that attackers used almost identical coordinated structures in this phase of spike performance. Nevertheless, the initial and end stages of spike movement have exhibited higher dissimilarity in movement patterns, which might imply that these phases are governed by distinct unified coordinated structures. These findings also support the concept that coordination variability rises during the acceleration phase of a highly competent player's throw-in performance (Button et al., 2003; Wagner et al., 2012). Besides, although individuals follow a unique movement patterning in every task, former studies highlighted higher flexibility in movement patterning among elite athletes (Travassos et al., 2013; Warren, 2006).

More diversities in the coordination patterning of all the players were found not only at the final phase of the spike phase but also at the beginning phase of the movement (from the plant phase start to the take-off). The attackers' performance was solely limited by their awareness throughout this phase, but from horizontal abduction until impact, the presence or absence of the blocks might have influenced their working memory during the execution of the motor program. More interestingly, cluster analysis revealed that practically all attackers moved in similar patterns dependent on their awareness of the existence or lack of defences. This shows that the awareness restrictions had a greater impact on spike performance coordinating patterning (particularly in the plant phase) than the block conditions. Due to which, any additional knowledge about the opponents' condition or performance may have an impact on athletic performance.

Two biomechanical theories exist in addition to the above-mentioned assumption. Due to the diversity of the thrown ball's spatial location, the attackers had to recreate the unified DOFs for each ball position individually, which increased the bandwidth of the current coordinated structure at each spike time (Button et al., 2003). Nonetheless, the coordination patterning shows that these differences were insufficient to totally separate the movement pattern in each condition. Such minor differences in coordination patterning during the spike's acceleration phase could indicate that the autonomous nervous system was in charge of the spike's acceleration phase performance, while some unified DOFs existed in the autonomous system as possible alternative options to be used immediately under different task constraints.

The second hypothesis, which is similar to the two above-mentioned hypotheses, focuses mostly on joint-space data (Kudo et al., 2000; McDonald et al., 1989). Due to the alterations in the accelerations phase of the arm and hand, which could be associated with the opponents’ block condition or tossed ball position, every joint constantly try to compensate the previously happened changes to stabilize the structure at the hitting moement. According to this assumption, the attackers' impact moment was positioned in the same spot in the coordination patterning of their spike performance. This backs up the idea that each joint's spatiotemporal location is determined by self-organization of the effective DOFs in order to perform the required action as effectively as feasible.

Furthermore, the outer layer of cluster analysis revealed that each participant's movement patterning was consistent across all situations. This finding demonstrates that, while being aware of future conditions may impact athletic performance, each player has his or her own unique coordination patterning, and there is no universal coordination patterning for spiking performance. As a result, the 'one-size-fits-all' training program paradigm, which is commonly used by volleyball coaches and trainers to teach their athletes regardless of their particular skills and motor learning capacity, seems necessary to be revised (Minett & Costello, 2015). These findings show that even players with identical game positions (e.g., wing spiker, center spiker, or opposite spiker) do not necessarily follow the same coordination patterning in their spike performance. Hence, using the same training regimen for all athletes, especially those at the elite or highly skilled levels, does not appear to be the greatest option for improving their performance.

To this end, the fourth hypothsis of this study was confirmed. **The whole body coordination patterning in spike performance is a unique among individuals.**

3.1 Limitations

During the measurement procedure, we instructed the defences to pretend to counter when they were asked not to block. Nevertheless, our observation showed that some defences have not been successful in the 'pretend-to-block' task, which might have affected the coordination pattering of the attackers in some not-blocked condition spikes. Another limitation was that two participants were left-handed; however, the motion capture system was set in a wider area to cover the entire playground.

A further limitation of this study was the participants' population (N=13), which may impact the statistical power and needed to be fully considered with caution. Nevertheless, only players from the national volleyball team in the U-17 category were recruited in this investigation. To this effect, our included sample could be characterised by relatively good homogeneity.

4 Conclusion

This dissertation provides insight into the techniques adopted by volleyball attackers to accomplish a successful spike performance in a real-game simulated condition. Although it has been abundantly claimed that jump height is the pivotal contributor to the successful spike performance, our results portrayed that this parameter is not the sole criterion for the accomplishment of a successful spike performance. In addition to the jump and spike altitudes, our results demonstrated that trunk extension rates and arm-swing velocities at take-off, and wrist velocities at the impact moment are the main contributors to the success rate among the players. Simply explained, a coordinated movement of knee extension with trunk extension and arm-swings (shoulder and elbow flexions) help in higher jump heights at take-off, while the spike velocity in the jump phase increases the success rates.

SOM and cluster analysis, in addition, illustrated that neither whole-body joints ROMs nor whole-body and lower-limbs joints angular velocities that contribute to the spike success rate, but it is upper-limbs angular velocities. Besides, reaching higher jump and spike altitudes could be the result of upper limbs coordinated movements, combined with lower limbs extensions. To this end, according to the discussion covered above, we could suggest the volleyball trainers and coaches mainly focus on technique development than pure explosive strength training to solely enhance jump heights among volleyball players. This suggestion could practically enhance players' spike success rate significantly because the strength training itself only focuses on the physical aspect of spike performance while learning a correct technique could cope with physical deficits to some extent. Thus, it is highly recommended to the trainers and coaches to design a skill-development training program that focuses on coordinated movement between the lower- and upper limbs for the acquisition of better jump performance, and a synchronized movement between upper limbs segments to reach a high spike velocity with high accuracy rates. Thus, it could be claimed that reaching to the minimum required jump heights is enough for executing a successful spike performance, as the upper-limb roles woud be more visible in success rate when the attacker is in the air. However, we do not suggest neglecting or undervaluing the necessity of jump height training programs among volleyball players.

Besides, the outcomes of the fourth study portrayed individualization in designing training programs for volleyball players. Although the trainers or coaches are suggested to focus on lower- and upper limbs coordination patterning technique in spike performance, we would like to suggest including these training programs into an individually-designed training program so that every player could make the most of her-his training program. This suggestion could be applied to individual- or position-specific (wing spikers, middle blockers, etc.) training programs.

5 Summary

A direct relation exists between the volleyball competition success rate and the attacking capacities of volleyball players. Several biomechanical characteristics (such as approach speed, jump height, etc.) are often highlighted as essential variables in the spike success rate. Despite this, there is a paucity of exact evidence in the literature on the main factors to the volleyball spike success rate. To this end, this thesis was conducted with the aim of investigating the biomechanical factors that contribute to the volleyball spike success rate among young elite volleyball players. Thirteen young Czech Republic national volleyball players (15.4±0.72years, 190.4±5.76cm, 76.2±5.66kg) with over 6 years of national and international experiences performed 12 volleyball spike with presence of 2 blocks, similar as a real-game condition. They, also, perforemd 3 countermovement jumps on a force platform. Outcomes revealed that peak and average rate of force developement, modified reactive strength index and concentric net impulse were the key kinetics elements in achieving higher spike jump heights. From kinematics point of view, the knee and hip extension angular velocities, vertical velocity of centre of mass, jump height, arm swing velocity at take-off and wrist velocity at the impact moment were the main contributors to the spike success rate. The Self-Organising map cluster analysis, in addition, highlighted that the upper limb velocities, compared to the lower limb velocities, have a significantly more impact on volleyball spike success rate among volleyball players. Results also showed that every player had his unique coordination profiling in spike performance. These outcomes revealed that reaching to the minimum required jump heights for a successful spike performance would be sufficient, as it is the upper limb performance (in the air) that acts as a key parameter in spike success rate. Nevertheless, the fact that the volleyball players need to enhance their jumping capacities should not be hided behind the outcomes of this study, since the players are obliged to jump efficiently before the ball impact moment. Thus, we recommend the coaches and athletes to shift their focuses towards the upper limb techniques in an individual-based training program, as well as enhancing jumping performance capacities.

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