UNIVERSITÀ DEGLI STUDI DI

CASSINO E DEL LAZIO MERIDIONALE

Corso di Dottorato in

Metodi, Modelli e Tecnologie per l'Ingegneria

curriculum Ambienti e tecnologie per l'attività motoria e la salute

Ciclo XXXII

Sex-dependent differences in the volleyball spike jump performance and specific technique training for female athletes

SSD: M-EDF/02 (Metodi e Didattiche delle Attività Sportive)

Coordinatore del Corso
Chiar.ma Prof.ssa Wilma Polini

Dottorando
Philip X. Fuchs

Supervisore
Chiar.ma Prof.ssa Cristina Cortis

I Acknowledgements

I want to express my gratitude for the opportunity to write the thesis of the joint PhD at the University of Cassino e Lazio Meridionale and the University of Salzburg. Without the support of many people and without the access to facilities, the cooperation and studies leading to this thesis would not have been possible.

Special thanks to Dr. Cristina Cortis for the cooperation, supervision, her availability, and great support in overall managing this joint PhD. Besides scientific work on manuscripts, this support also included organization of courses, administrative tasks, and even housing, which severely facilitated my stays in Cassino.

I am also grateful for the close contact and cooperation with Dr. Andrea Fusco and the exchange with him about methods and statistics as well as the data collection and processing that we conducted together.

Lecturers, other PhD students, and eventually administrative staff at the University of Cassino e Lazio Meridionale allowed the implementation of this joint PhD, a fruitful cooperation, and sharpening my knowledge and skills.

Overall, I very much appreciate the people that have been engaged in this project and that I met in Cassino, making this journey a special and unforgettable experience.

Dr. Herbert Wagner, furthermore, was available as tutor in Salzburg whenever required and enabled the access to required facilities for data collection.

The female and male teams of the volleyball club in Salzburg ‘PSV’ participated in the studies. The female players, who participated in a training intervention study, were highly motivated and focused during the training sessions.

Without the support and outstanding tolerance of two social key persons (Jana Paul, Maik Schätzel), it would have taken much more time to finalize the thesis and most likely would have caused more severe losses: Special thanks for the food supply while I was able to keep up working.

Salzburg, February 2020

II Affidavit

Unless differently stated in the text, references, or acknowledgments, this thesis is the product of my own work. Therefore, I take full responsibility for inaccuracies and faults. This thesis is not submitted for another degree at this or any other institution. The printed version of the thesis is equivalent to the submitted electronic one.

Salzburg, February 2020 Philip X. Fuchs, M.Sc.

III Preface – List of publications

This cumulative Ph.D. thesis is based on research investigations conducted at the Department of Sport Science and Kinesiology, University of Salzburg, Salzburg, Austria from 2015 to 2019. The single studies have been submitted as original research manuscripts to international peer-reviewed journals. The third manuscript was added to this thesis as the clean version of the most recent resubmitted major revision.

I. Fuchs, P. X., Menzel, H.-J. K., Guidotti, F., Bell, J., von Duvillard, S. P., & Wagner, H. (2019). Spike jump biomechanics in male versus female elite volleyball players. *Journal of Sports Sciences, 37*(21), 2411-2419.

II. Fuchs, P. X., Fusco, A., Bell, J. W., von Duvillard, S. P., Cortis, C., & Wagner, H. (2019). Movement characteristics of volleyball spike jump performance in females. *Journal of Science and Medicine in Sport, 22*(7), 833-837.

III. Fuchs, P. X., Fusco, A., Bell, J. W., von Duvillard, S. P., Cortis, C., & Wagner, H. (accepted). The effect of Differential Training on female volleyball spike jump technique and performance. *International Journal of Sports Physiology and Performance*.

Additional studies, which do not relate to this thesis, were published in international peer-reviewed journals. Three of them were implemented in cooperation with the University of Cassino e Lazio Meridionale, Italy.

1. Fuchs, P. X., Wagner, H., Hannola, H, Niemisalo, N., Pehme, A., Puhke, R., Marinsek, M., Strmecki, A., Svetec, D., Brown, A., Capranica, L., & Guidotti, F. (2016). European student-athletes' perceptions on dual career outcomes and services. *Kinesiologia Slovenica, 22*(2), 31-48.
2. Fuchs, P. X., Lindinger, S. J., & Schwameder, H. (2018). Kinematic analysis of proximal-to-distal and simultaneous motion sequencing of straight punches. *Sports Biomechanics, 17*(4), 512-530.
3. Wagner, H., Fuchs, P. X., & von Duvillard, S. P. (2018). Specific physiological and biomechanical performance in elite, sub-elite and in non-elite male team handball players. *Journal of Sports Medicine and Physical Fitness, 58*(1-2), 73-81.

4. Fusco, A., Giancotti, G. F., Fuchs, P. X., Wagner, H., Varalda, C., Capranica, L., & Cortis, C. (2018). Dynamic Balance Evaluation: Reliability and Validity of a Computerized Wobble Board. *The Journal of Strength and Conditioning Research*. DOI: 10.1519/JSC.0000000000002518
5. Wagner, H., Fuchs, P., Fusco, A., Fuchs, P. X., Bell, J., & von Duvillard, S. P. (2019). Physical performance in elite male and female team handball players. *International Journal of Sports Physiology and Performance, 14*(1), 60-67.
6. Fusco, A., Giancotti, G. F., Fuchs, P. X., Wagner, H., Varalda, C., & Cortis, C. (2019). Wobble board balance assessment in subjects with chronic ankle instability. *Gait & Posture, 68,* 352-356.
7. Fusco, A., Giancotti, G. F., Fuchs, P. X., Wagner, H., Rubens, D. S., & Cortis, C. (2020). Y balance test: Are we doing it right? *Journal of Science and Medicine in Sport*, *23*(2), 194-199.

IV Abstract

Despite the importance of the spike jump in volleyball and the high number of female athletes at high level, movement analyses of the volleyball spike jump were mainly conducted in male players. Potential sex-dependent differences were marginally considered in the scientific literature and practical training. The few studies that tackled this problem can, due to limitations, only hint on the existence of sex differences in essential movement characteristics. Investigations on factors that determine performance in females are also lacking; frequently, performance determinants found in males were assumed to be identical in female players. Consequently, sex-specific training measures to improve technical movement characteristics in the volleyball spike jump are not common. The purpose of this dissertation was 1) to investigate sex-specific differences in movement characteristics, 2) to identify performance determinants in females, and 3) to implement and assess a specific technical training to enhance volleyball spike jump performance in female players.

One female and one male team (n_1=15, n_2=15) competing in the highest Austrian division were recorded via 12 Vicon MX-13 (250 Hz) cameras, two AMTI force plates (2000 Hz), and surface electromyography (2000 Hz) in 5 lower limb muscles. They performed volleyball spike jumps striking a stationary ball and the data was assessed to identify sex differences and performance determinants in females. Based on these findings, a specific six-week training intervention was derived and implemented for female players (n=12). Kinematic and kinetic data were obtained during three measurement sessions with six weeks between the sessions to allow for a comparison between control and intervention phase.

Significant (p<.05) sex differences were documented in approach, arm and torso usage, neuromuscular activation pattern, range of motion and acceleration distances, and the strategy to convert horizontal into vertical velocity. Correlation and regression analyses revealed that a majority of these variables affected jump height in females. A subsequent technical-coordinative training intervention that specifically focused on the relevant movement characteristics improved jump height by 11.9% during the competitive season. The intervention resulted in beneficial adaptations in all measured movement characteristics that were not strictly related to strength and power abilities.

The sex differences corroborated that technical patterns identified on the basis of a sample that consists of males only cannot be assumed to be identical in females without any further investigation. The second study showed that several characteristics where differences

have been found affected spike jump performance in female players. Therefore, they should not be ignored and, instead, addressed in specific training measures. The training intervention study reported positive effects of such approach. The training measure applied in this study showed to effectively enhance female spike jump performance at high level in a short amount of time. However, this training approach requires biomechanical understanding of performance determinants from the coach and specific adaptations to the target group.

V Abbreviations

Δt	Time difference
3D	Three dimensional
CoM	Center of mass
CSA	Cross-sectional area
D	Dominant side (right side for right-handed players)
EMG	Electromyography
FIVB	Fédération Internationale de Volleyball
FP1 / FP2	Force plate 1 (=FPF) / Force plate 2 (FPR)
FPF / FPR	Force plate front (=FP1) / Force plate rear (FP2)
GRF	Ground reaction force
ND	Non-dominant side (left side for right-handed players)
RFD	Rate of force development
RoM	Range of motion

VI Table of Content

I Acknowledgements ii

II Affidavit iii

III Preface – List of publications iv

IV Abstract vi

V Abbreviations viii

VI Table of Content ix

1 Introduction 1

2 Mechanisms of the volleyball spike jump 2

3 Sex differences in performance and technique 4

4 Training intervention 7

5 Research deficit 10

6 Aim of the thesis 12

ARTICLE 1 13

ARTICLE 2 23

ARTICLE 3 29

7 Summary and perspectives 49

8 Tables 51

9 Figures 52

10 References 53

1 Introduction

Volleyball is a popular sport across the globe and represented by 222 affiliated federations of the Fédération Internationale de Volleyball worldwide (FIVB, 2019). It is an Olympic sport that, unlike other sports, is played competitively at high levels by both sexes. However, volleyball seems to attract females more than males as the number of female athletes is higher. The well-documented statistics by The National Federation of State High School Associations (2018) show that 88% of the volleyball competitors at US high school level were females.

In volleyball, two teams play on a court divided in halves by a net in the middle. The goal is to score points by maneuvering the ball over the net so that the opposing team is not able to prevent the ball from hitting the ground. Great ball velocity increases the likelihood to score because it reduces the reaction time for the opponent. With increased ball velocity, the trajectory of the ball approximates a straight line rather than a curve. To spike the ball with high velocity (which implies a nearly straight ball trajectory) into the limited opponent's half of the court, it is required to strike the ball when its position is higher than the net. Moreover, higher ball position at the time of striking enlarges the effective field size that the ball can be stroke into following a steep trajectory. This forces the opponent team to cover a wider area of the field and makes it more difficult to defend the attack.

This explains why the spike jump is the most frequently used offensive action and considered most decisive for winning matches (Palao, Santos, & Ureña, 2004). Furthermore, it demonstrates the importance of great spike velocity and jump height. The latter is not only relevant in spiking but also in blocking, another key action in volleyball. Unlike in other sports such as soccer where jump height is beneficial but deficits can be compensated by adapting the play style (e.g. preferring dribbling or low passes), this is not possible in high level volleyball. In volleyball competition, an offensive player attempts to achieve great jump height to ensure various actions and to be less predictable. That is why jump height is a main target in volleyball training (Powers, 1996). And in fact, both jump height and ball velocity are fundamental performance criteria and were found to correlate with overall competition level (Forthomme, Croisier, Ciccarone, Crielaard, & Cloes, 2005; Sattler, Hadžic, Dervišević, & Markovic, 2015; Ziv & Lidor, 2010).

2 Mechanisms of the volleyball spike jump

The spike jump is a very specific and complex jumping movement influenced by the technical skills of the players. It is characterized by the dynamic approach, coordination between lower limb extension and arm swing, asymmetric positions and roles of legs and arms. Theory based descriptions in the literature (Tilp, 2003; Viera & Ferguson, 1989; Waite, 2009), explain the volleyball spike jump as follows:

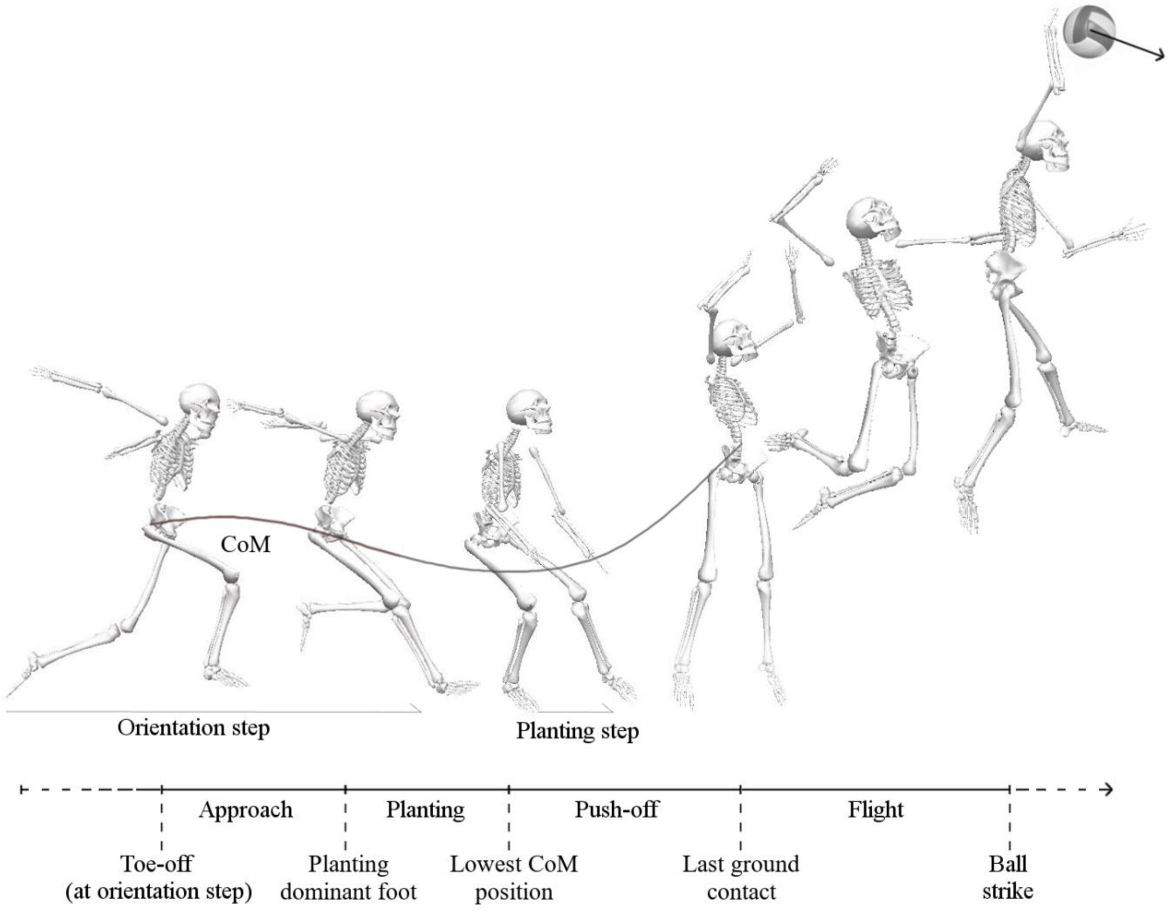
> The volleyball spike jump starts with an approach to develop horizontal speed. A 3-step or 4-step approach is commonly used, depending on the situation and the athlete's preference. The last two steps are the most essential ones and do not differ between the 3- and the 4-step approach. The orientation (/penultimate) step is a powerful and long step that contributes to the horizontal speed. In the same time, both arms swing backwards in a wide range of motion to prepare a dynamic arm swing for the actual jump. The plant (/last) step is short and places one foot parallel to the other. Ideally for the upwards acceleration during push-off, the distance between the feet is not larger than the width of the hip to allow straight alignment of the legs in vertical direction. Despite parallel placement of the feet, the plant foot is sometimes also referred as front foot because of hip rotation during the approach, which prepares the actual strike. This is the reason for asymmetry in feet position and leg functionality in the spike jump. During the orientation step,
>
> 1) the push-off through the non-dominant leg increases horizontal speed,
> 2) arm swing is initiated to generate momentum and enhance ground reaction forces,
> 3) the torso is inclined and lower limb joint angles (i.e. hips, knees, ankles) decrease, which lowers the center of body mass (CoM) and results in a countermovement of the body, and
> 4) the planted dominant leg reduces horizontal velocity and transfers it into vertical direction. The non-dominant leg contributes to the velocity conversion during the plant step (due to the asymmetry in legs, they operate and fulfill this task in different fashions).
>
> As lower limb joint angles decrease and leg extensors get stretched, the extensor muscles work eccentrically to stop the horizontal speed and transition into subsequent concentric contraction. This phenomenon is called stretch-shortening-cycle and leads to higher force levels in the beginning of upwards movement of the

CoM and higher impulse to accelerate the body. The countermovement displaces the CoM vertically and, thus, increases the distance of acceleration for the push-off. The beginning of the push-off phase is defined as the lowest position of the CoM.

Experimental research reported proximal-to-distal muscle activation pattern and timing of maximal joint velocities of the lower limbs to maximize ground reaction forces and jump height (Bobbert & van Ingen Schenau, 1988). Also the importance of approach speed, countermovement, knee angles, and arm swing was observed (Wagner, Tilp, von Duvillard, & Müller, 2009).

During the flight phase, momentum generated in the pelvis and torso contribute to great angular velocities in the shoulder flexion and internal rotation, elbow extension, and finally to the spike velocity (Wagner et al., 2014).

Figure 1. Volleyball spike jump from approach to strike. The visualization depicts a computed 3D-model on the basis of kinematic data of a male right-handed player and the calculation of CoM during approach until take-off to derive approach speed and jump height via CoM velocity.

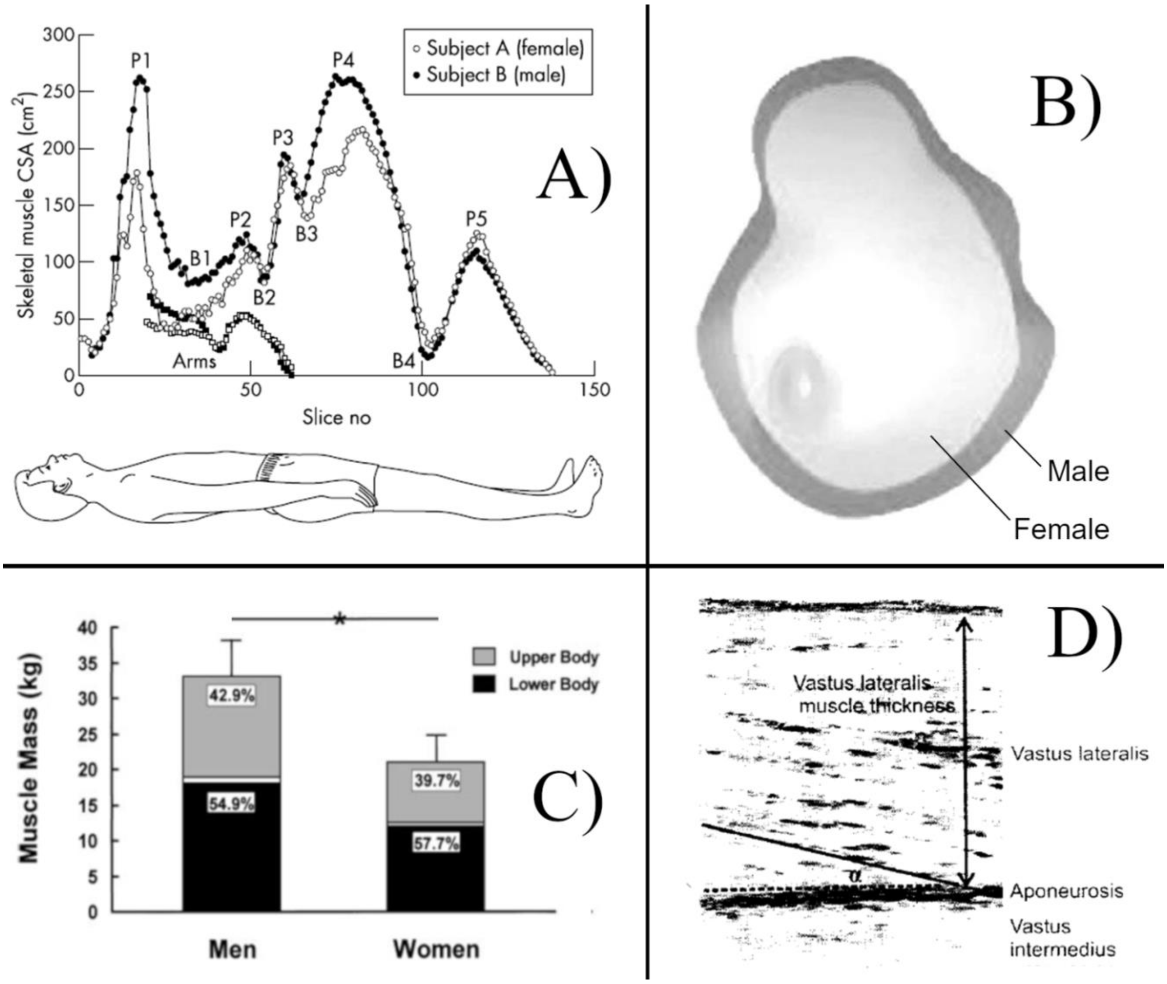


Note: CoM=center of body mass; dominant=the side of the striking arm.

3 Sex differences in performance and technique

Although jump height is a performance determinant for both females and males, there is a difference in jump height between sexes (Alegre, Lara, Elvira, & Aguado, 2009). Previous research documented multiple sex-dependent biological differences that affect sports performance. These included body mass, distribution and proportion of skeletal muscles (Abe, Brechue, Fujita, & Brown, 1998; Abe, Kearns, & Fukunaga, 2003), muscle size (Janssen, Heymsfield, Wang, & Ross, 2000) and cross-sectional area (Häkkinen & Pakarinen, 1993), muscle morphology (Alegre et al., 2009), pennation angles in the musculus vastus lateralis and musculus gastrocnemius medialis (Abián, Alegre, Lara, Rubio, & Aguado, 2008), and anatomy of the shoulder joint (Merrill, Guzman, & Miller, 2009).

Figure 2. Biological sex differences in A) the distribution of muscle cross-sectional area, B) glenoid size and shape, C) muscle mass in upper and lower body, and D) muscle architecture in the lower limbs.



Note: The figure is a merged adaptation on the basis of visualizations from Abe et al. (2003), Alegre et al. (2009), Janssen et al. (2000), and Merrill et al. (2009).

Males seem to have some biological advantages in many sports settings. Hence, some authors see the reason for performance differences exclusively in anthropometry and strength abilities (Nelson, Thomas, Nelson, & Abraham, 1986; Thomas & French, 1985). However, another possible cause may be technical-coordinative variations of movement characteristics between sexes. These are documented in various basic movements such as walking (Chumanov, Wall-Scheffler, & Heiderscheit, 2008; Kerrigan, Todd, & Croce, 1998), running (Chiu & Wang, 2007; Ferber, Davis, & Williams III, 2003), and throwing (Chu, Fleisig, Simpson, & Andrews, 2009; Liu, Leigh, & Yu, 2009).

Table 1. Examples for sex differences in characteristics during basic movements.

Movement	**Reference**	**Differences between sexes**
Walking	Chumanov et al. (2008)	Maximal hip internal rotation and adduction, lower limb muscle activation
	Kerrigan et al. (1998)	Hip and knee angles, knee moments and power
Running	Chiu and Wang (2007)	Tibialis anterior activity, ankle angle
	Ferber et al. (2003)	Maximal hip internal rotation and adduction
Throwing	Chu et al. (2009)	Stride length, foot placement, upper torso/pelvis separation
	Liu et al. (2009)	Sequence of shoulder abduction and adduction

This can also be expected in jumping as sex differences in the alignment of hip and knee joints were reported and authors assumed that it may affect dynamic movement patterns of the lower limbs (Nguyen & Shultz, 2007). Moreover, sex differences in elastic properties of the vastus lateralis tendon-aponeurosis complex affect the force transmission and countermovement jump height (Bojsen-Møller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005). In countermovement jumps, females demonstrate less vertical CoM displacement during the eccentric and concentric phases (McMahon, Rej, & Comfort, 2017). The authors concluded a differential leg stiffness strategy. Laffaye, Wagner, and Tombleson (2014) confirmed sports-specific differences in ground reaction forces (GRF) between sexes during general countermovement jumps. The temporal structure of jumping (i.e. relative duration of phases) showed no sex differences, contrary to the absolute and normalized eccentric rate of force development (RFD). Moreover, correlation results of the duration of the eccentric phase and normalized eccentric RFD with jump height differed between sexes. The data revealed sport-specific characteristics in GRF profiles that allowed the authors to classify the data and to associate specific patterns with particular sports. The researchers derived different clusters of GRF profiles for different types of sports. This corroborates that athletes develop sports-specific patterns when performing a countermovement jump and implies that jumping must be analyzed specifically for different sports. The patterns observed in this study differed between types of sports and also between sexes; and the authors successfully predicted the practiced type of sports and sex of an athlete on the basis of GRF characteristics. Regarding sports-specific jumping tasks, sex differences in movement characteristics were found in soccer (Yu et al., 2005) and volleyball (Chen, Huang, & Shih, 2011). Chen et al. (2011) suggested that technical aspects such as approach speed, knee angles, and upper body lean may limit female spike jump performance in volleyball. Sattler et al. (2015) also analyzed volleyball spike jumps and detected potential improvement in the female arm swing, which is considered to affect jump height (Lees, Vanrenterghem, & De Clercq, 2004). As Ikeda, Sasaki, Sorimachi, and Hamano (2017) reported, multiple of these variables relate with female jump height.

4 Training intervention

Sex-specific training is a corollary of the sex differences observed in biology, movement patterns, and performance. Traditional strength and power training is the most frequently applied option to increase jump performance in volleyball (Powers, 1996; Ziv & Lidor, 2010). However, as differences were expected in movement characteristics that determine technique and coordination, additional technical training interventions should be considered. To my best knowledge, sex-specific technical training to increase spike jump height is not well established in the current literature and volleyball practice. To develop training measures that induce technical and coordinative adaptations, it is important to understand the following about motor control and motor learning.

Motor learning can be simplified as a model of three stages (Baumann & Reim, 1994). Each of the stages represents signal processing and movement regulation in different neuronal areas on the basis of external and internal feedback stimuli, comparably displayed in the Closed-Loop theory (Adams, 1976).

> During the first stage, the movement is mainly performed at conscious levels. The motor cortex in the central nervous system sends signals to the effector organs; there is limited internal feedback. Feedback consists of comments from the coach and the athlete’s observation of success and failure.
>
> At the second stage, unconscious processes in sub-cortical areas contribute to movement regulation by providing internal information (e.g. from kinesthetic receptors). This information relieves conscious processes that can now focus on specific elements of the movement.
>
> Lastly, spinal and supra-spinal areas of the nervous system begin to take over the unconscious regulation of posture and muscle tone and allow for reactive mechanisms.

Over the span of the learning progress from beginner to expert, these three stages are not involved simultaneously from the beginning but are more strongly engaged one after another. With increasing skill, more internal feedback is involved in the learning process and movement regulation. Important internal feedback can be summarized as kinesthetic signals (e.g. from muscles), the sense of balance and spatial orientation (vestibular system), and tactile information (skin). External plus internal feedback describes the athlete’s current performance.

In traditional motor learning approaches, an ideal model (external instruction) is presented to the athlete who attempts to replicate it. With each repetition, the athlete assesses the current performance, compares it with the model, and tries to imitate it. The basic idea of traditional, repetitive motor learning approaches is to reduce the difference between current execution and the ideal model (Schöllhorn, Hegen, & Davids, 2012). Another key characteristic of traditional perspectives (e.g. Fitts & Posner, 1967) is the suggested linearity between movement and performance variability. The training goal is the reduction of movement variability to achieve reduced performance variability and, hereby, more consistent performance. This seems reasonable during beginner and intermediate stages of learning when appropriate 'coordination' and 'control' (Newell, 1985) are lacking.

However, Bernstein (1967) showed that a specific movement is never repeated twice and movement variability is unavoidable. The performance outcome may be repeated identically but the movement characteristics vary. Microscopic movement variability is the result of unconscious fine regulation of the movement based on internal feedback. It enables the athlete to stabilize the movement outcome despite external interference and to exploit the unique dynamics of various situations to the own benefit (Bernstein, 1967; Hamill, van Emmerik, Heiderscheit, & Li, 1999; van Emmerik & van Wegen, 2000). This indicates the relevance of movement variability in high level performers, which is also supported by Wilson, Simpson, van Emmerik, and Hamill (2008). In fact, variable movement patterns were observed in elite athletes (Davids, Glazier, Araujo, & Bartlett, 2003). Moreover, Bartlett, Wheat, and Robins (2007) reported increased movement variability in skilled players' distal joints, which are responsible for fine regulation and adaptation to situational demands, across sports. Therefore, variability is essential in motor control (Dhawale, Smith, & Ölveczky, 2017) and should be integrated in motor learning strategies, especially at high levels and in dynamic and complex situations.

Consequently, imitating a predefined model under stabile and simplified conditions seems to be an outdated strategy to develop highest skills that are transferable to the dynamic situations of sports competitions. An alternative approach is differential training (Schöllhorn et al., 2012), which showed superior effects compared with traditional training concepts (Römer, Schöllhorn, Jaitner, & Preiss, 2009; Savelsbergh, Kamper, Rabius, De Koning, & Schöllhorn, 2010; Schöllhorn et al., 2012). The basic idea is to increase the variety of experiences of the athlete how to solve a specific movement task under various conditions. Hereby, conscious processing is not required from the athlete. Instead, the neuronal system interpolates between the numerous experiences automatically. This leads to unconscious self-regulation and adapted movement patterns and supports the identification of individualized optimal coordination at microscopic levels. Therefore, differential training seems to be a promising approach to increase technical-coordinative skills at high levels in dynamic scenarios.

5 Research deficit

Experimental studies investigating sex differences in sports-specific (particularly volleyball) jumping movements are rare (Ziv & Lidor, 2010) and a sufficient amount of information and data was not found. In the few documented cases, the impact of movement characteristics on performance was not tested but assessed on a theoretical basis only. Previous intervention studies involved traditional strength and power training (Fatouros et al., 2000), ballistic and plyometric training (Markovic, 2007; Martel, Harmer, Logan, & Parker, 2005; Newton, Kraemer, & Haekkinen, 1999; Newton, Rogers, Volek, Häkkinen, & Kraemer, 2006), the application of electro-stimulation (Maffiuletti, Dugnani, Folz, Di, & Mauro, 2002; Malatesta, Cattaneo, Dugnani, & Maffiuletti, 2003) but, to my knowledge, never considered differential training focused on technique to optimize jump height.

Table 2. Studies that investigated sex differences or effects on female volleyball jump performance.

Reference	**Limitation**
Chen et al. (2011)	Kinematics only Small sample size (n_1=6, n_2=6) Only conference report available
Sattler et al. (2015)	No collection of arm swing and approach data but, instead, comparing jump height with/without arm swing and with/without approach (only the resulting jump height was assessed; no insights beside difference in height)
Ikeda et al. (2017)	Beside CoM and its deceleration, little insights in technique (mainly angular velocities, power, and work investigated)
Hsieh and Christiansen (2010)	Kinematics only Female sample only; assessment of sex difference on the basis of comparison with literature using male sample but other methods Small sample size (n=10)
Hsieh and Heise (2008)	Comparing jump height between two skill levels instead of investigating relationships (e.g. based on correlation/regressions) Only conference report available

The existing literature does not display sex differences in spike jump mechanics and the effect on female performance sufficiently as previous studies share at least one of the following limitations: They were conducted with critically small sample sizes considering the performed statistical analyses; they were published only as conference reports with limited information; they collected only kinematic data; they investigated few key variables not allowing for insights on the variables' role and the resultant effect on the movement.

Another problem is that research in volleyball, like in other sports, was mostly implemented based on male samples (Forthomme et al., 2005; Wagner et al., 2009). Performance factors in females were investigated marginally. The assumption that females and males share the same ideal movement characteristics and determinants is widely spread in the scientific and coaching community. For example, in the assessment of female performance, Hsieh and Heise (2008) referred multiple times to findings based on a male sample (Lees et al., 2004), building their interpretation on specific percentage values observed in males. However, there is no confirmation at this stage. This means that, in fact, it is unclear which characteristics a technical training intervention in females should aim for. In practice, females train in similar fashions compared with males (accounting for differences in strength and power) and aim to achieve the same movement patterns, which may not be the ideal technique.

Knowledge of performance factors is the most fundamental prerequisite to develop specific training measures but is lacking in females. Especially traditional training approaches build on the knowledge of optimal movement patterns and performance determinants. Only then, an ideal model of the target movement can be derived, described, and imitated by the athlete. Differential training does not rely on a strict, predefined model for replication. However, such training approach was never investigated in high level female volleyball spike jumping and is lacking in the sports literature.

Therefore, the investigation of sex differences in movement characteristics and the influence on performance would fill the lack in the current state of research. This allows the development and testing of a sex-specific training intervention in a context that was never reported in the literature to this point.

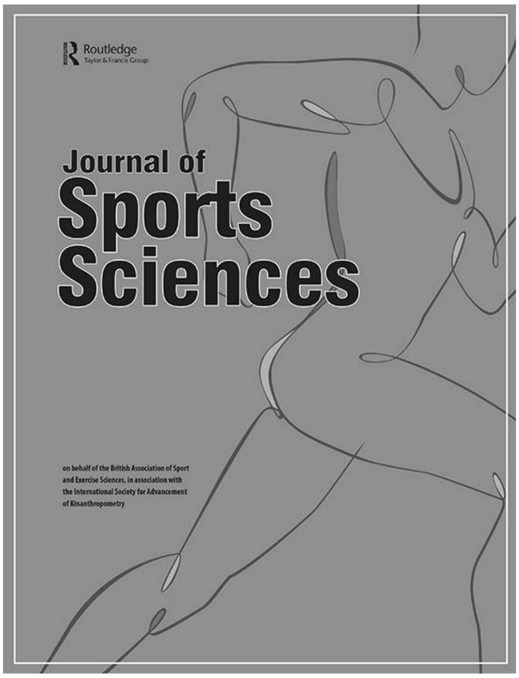
6 Aim of the thesis

The first aim of this doctoral thesis is to analyze kinematic, kinetic, and neuromuscular characteristics of females and males in volleyball spike jumping to holistically comprehend the differences between sexes.

The second aim is to investigate the influence of movement characteristics on female performance and to identify performance determinants.

The third aim is 1) to develop and implement a specific training intervention for female volleyball players and 2) to assess its effects on movement characteristics and performance. The goal of such intervention is to increase jump performance thanks to the enhancement of technical movement criteria.

ARTICLE 1



Impact Factor (2018): 2.811

Fuchs, P. X., Menzel, H.-J. K., Guidotti, F., Bell, J., von Duvillard, S. P., & Wagner, H. (2019).

Spike jump biomechanics in male versus female elite volleyball players.

Journal of Sports Sciences, *37*(21), 2411-2419.

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2019.1639437

Routledge
Taylor & Francis Group

SPORTS PERFORMANCE

Check for updates

Spike jump biomechanics in male versus female elite volleyball players

Philip X. Fuchs [a,b], Hans-Joachim Karl Menzel [c], Flavia Guidotti[d], Jeffrey Bell[e], Serge P. von Duvillard[a] and Herbert Wagner[a]

[a]Department of Sport Science and Kinesiology, University of Salzburg, Salzburg, Austria; [b]Department of Human Sciences, Society and Health, University of Cassino and Lazio Meridionale, Cassino, Italy; [c]Departamento de Esportes, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil; [d]Department of Movement, Human and Health Sciences, University of Rome Foro Italico, Rome, Italy; [e]Science Department, Southwest Minnesota State University, Marshall, MN, USA

ABSTRACT

There are well-known biological differences between women and men, especially in technical-coordinative variations that contribute to sex differences in performance of complex movements like the most important offensive action in volleyball, the spike jump. The aim of this study was to investigate sex-dependent performance and biomechanical characteristics in the volleyball spike jump. Thirty female and male sub-elite volleyball players were analysed while striking a stationary ball with maximal spike jump height. Twelve MX13 Vicon cameras with a cluster marker set, two AMTI force plates, surface EMG, and a Full-Body 3D model in Visual3D were used. Main findings include sex differences ($P < .05$) in jump height ($p\eta^2 = .73$), approach [speed ($p\eta^2 = .61$), step length], transition strategy [plant angle, neuromuscular activation ($p\eta^2 = .91$), horizontal force maxima and impulses], acceleration distances [centre of mass displacement ($p\eta^2 = .21$), minimal knee and hip angles], use of torso and arms [incline, angular velocity ($p\eta^2 = .23$)]. Correlations support that the results cannot be explained fully by strength and power differences between sexes but represent the product of technical-coordinative variations. Their relevance is acknowledged for both sexes and numerous performance determinants displayed sex differences. The integration of such attributes into sex-specific training seems promising but its effect requires further investigation.

ARTICLE HISTORY
Accepted 25 June 2019

KEYWORDS
Three-Dimensional (3D) analysis; kinesiology; kinetics; sex; performance

Introduction

Volleyball is an Olympic sport that is played in more than 200 countries in the world. Volleyball uses several complex movements in offense and defence. However, the spike typically finalises the offensive action and is one of the most important and basic techniques (Drikos, Kountouris, Laios, & Laios, 2009). In the spike, the goal of an offensive player is to achieve great jumping height to be unpredictable and ensure diverse actions. The higher the player's jumping height during the spike, the larger the effective field size and the steeper the ball trajectory at high ball velocity. In previous studies, it was found that jumping performance correlates with competition level (Sattler, Hadžic, Dervišević, & Markovic, 2015; Ziv & Lidor, 2010). Consequently, achieving great jumping height is a determining factor in female and male volleyball performance (Ziv & Lidor, 2010).

The jump used during the spike is a very specific and complex jumping movement. Its performance is not only determined by the player's strength and power but also influenced by technique and coordination. Descriptions of the volleyball spike jump (Viera & Ferguson, 1989; Waite, 2009) can be summarised as follows: during the approach phase, horizontal speed is developed and subsequently decelerated by planting one foot in front of the body. Dynamic arm swing allows to generate momentum and greater ground reaction forces. Lower limb muscles are pre-activated after planting the foot via a stretch-shortening-cycle, joint angles decrease and the body is lowered in a countermovement to increase the distance during acceleration. Correct activation timing of the lower limb muscles is crucial for coordination pattern that maximises ground reaction forces and thus jump height (Bobbert & van Ingen Schenau, 1988). Experimental research has confirmed the importance of approach speed, countermovement, knee angles, and arm swing (Wagner, Tilp, von Duvillard, & Müller, 2009). All of the above-mentioned aspects of the spike jump movements reflect biomechanical variables that are of special interest to our study since their importance for jump performance has been reported in the scientific literature. The assessment of relevant biomechanical factors of performance is essential for appropriate training progression, especially at high skill levels.

Volleyball is played at the professional level by both females and males. However, optimal force mechanisms and motion characteristics have largely been reported based on studies of male athletes or have not considered sex differences. Technical-coordinative variations of motion characteristics between sexes may be one factor leading to performance differences and have been documented in various basic movements such as walking (Chumanov, Wall-Scheffler, & Heiderscheit, 2008; Kerrigan, Todd, & Croce, 1998), running (Chiu & Wang, 2007; Ferber, Davis, & Williams III, 2003), and throwing (Chu, Fleisig, Simpson, & Andrews,

CONTACT Philip X. Fuchs philip.fuchs@sbg.ac.at @PhilipXFuchs Department of Sport Science and Kinesiology, University of Salzburg, Rifer Schlossallee 49, Hallein/Rif, Salzburg 5400, Austria

2009; Liu, Leigh, & Yu, 2009). By considering sex-dependent motion differences in the spike jump biomechanics, training can be improved to make performance more effective and efficient. Walsh, Böhm, Butterfield, and Santhosam (2007) addressed sex differences in arm swing and countermovement during basic jumping movements. However, a review of 26 studies (Bruton, O'Dwyer, & Adams, 2013) could not generalise sex-dependent differences in basic jumping motion characteristics across sports, but the data hinted at the existence of sex-dependent differences within specific sports. Laffaye, Wagner, and Tombleson (2014) reported sport specific sex differences in basic jumping motion based on ground reaction forces.

Regarding the volleyball spike jump, Hsieh and Christiansen (2010) indicated technique-related differences in approach speed between sexes by comparing their findings using female players with previous findings utilising only male players. Chen, Huang, and Shih (2011) suggested that approach speed, knee angles, and upper body lean may limit females' spike jump. Sattler et al. (2015) reported no differences in approach speed but did conclude that women's arm swing may need improvement relative to men's. The differences in male versus female arm swing may be important because arm swing mechanics are considered to affect jump height (Lees, Vanrenterghem, & De Clercq, 2004). The above listed studies address the effect of biomechanical factors on performance. However, the findings do not fully capture sex differences in spike jump mechanics since they share the following limitations: they collected only kinematic data, some did not analyse all phases of the spike jump, and the studies investigated few key variables which prevented insights on the variables' role and the resultant effect on the movement.

Deriving from previously reported descriptions and experimental studies, the primary aspects affecting jump performance are approach velocity, countermovement, upper body lean, arm swing and knee extension. Additionally, secondary variables also support and contribute to understanding of this occurrence. Secondary variables characterise the previously mentioned primary aspects and are presumed to interact with a primary variable (e.g., step length, plant angle, and horizontal forces relate to approach velocity). They support the holistic assessment of differences in primary characteristics. Consequently, the aim of the current study was to determine 1) the relationship between primary variables and jump height, 2) the interaction of secondary variables, and 3) sex differences in the primary attributes of volleyball spike jumping. We hypothesised to find significant sex differences in jump performance and the primary performance determinants.

Methods

Participants

One women's and one men's indoor volleyball team from the highest division in Austria were invited to participate in the present study. The close positions in the FIVB (2016) indicate a similar experience level of both teams. Each team's roster consisted of 15 athletes (including 2 setters and 1–2 libero) and their physical and experience characteristics are summarised here: 15 women (age: 19.9 ± 3.5 years, body height: 1.79 ± 0.06 m, body weight: 70.5 ± 11 kg, reach height: 2.27 ± 0.08 m, training experience: 8.4 ± 3.9 years, training hours per week: 11.5 ± 2.2 h) and 15 men (age: 22.7 ± 4.3 years, body height: 1.88 ± 0.06 m, body weight: 80.9 ± 6.7 kg, reach height: 2.43 ± 0.07 m, training experience: 10.1 ± 5.9 years, training hours per week: 10.9 ± 4.3 h). All participants were physically healthy and reported no injuries during the time of the study. The local ethics committee approved the research protocol in accordance with the Declaration of Helsinki, and all participants reviewed and signed informed consent before participation. For participants under 18 years of age, parental consent was obtained.

Test procedure

After a general and specific warm-up under the supervision of a member of the research unit, the participants executed as many test trials as needed to become familiarised with the upcoming task. They were requested to perform 10 valid spike jumps, jumping as high as possible and spiking a ball suspended from a rope from the ceiling as hard as possible into a marked field on the ground. The optimal ball position was found during the test trials to warrant best jump performance. To prevent fatigue, a 1-min rest was given between each trial. A spike jump was considered valid if the athletes' feet hit the two force plates on the ground separately and if the athletes and the test instructor decided that the highest jump height was reached. The participants were free to choose their optimal approach distance and angle.

Data capture and processing

For kinematic analysis, 12 Vicon MX-13 cameras (Vicon, Oxford Metrics, Ltd., UK) captured 51 reflective markers of 14 mm diameter with a measuring frequency of 250 Hz. The anatomical landmark calibration technique was performed using a Cleveland Clinical Marker set (Motion Analysis Corp, Santa Rosa, CA) with clusters on the lower limbs (Selbie, Hammil, & Kepple, 2013). Data were managed via Nexus 1.8. software (Vicon, Oxford Metrics, Ltd., UK) and filtered according to Woltring (1986). The calculation of segmental movements and further analyses were performed via Visual3D software (C-Motion, Inc., Rockville, MD). The definition of segments and the model were in agreement with specifications for the Cleveland Clinical Marker set using a segment's proximal and distal joint centres. The centre of body mass (CoM) was calculated in Visual3D based on segment positions and regression equations from Dempster (1955). Visual3D estimates net internal moments via inverse dynamics and segment inertia computed from segment masses, proximal and distal radii, and segment geometry (Dempster, 1955; Hanavan, 1964).

A global coordinate system was defined with the z-axis vertical in an upward direction and the x- and y-axes spanning a horizontal plane perpendicular to the z-axis. Flexion/extension in the knees, hips, and shoulders were calculated through the sagittal change of angle between the segments adjacent to the corresponding joint (ankle: foot-shank, knee: shank-thigh, hip: thigh-torso, shoulder: upper arm-torso).

For kinetics, two separate AMTI force plates (AMTI, Watertown, MA) collected ground reaction forces at 2000 Hz. The plates (120x60 cm) were placed parallel to each other with a 60 cm offset to enable the participants to place each foot on one force plate (FP1/2) naturally. A fourth-order low-pass Butterworth filter was used at 50 Hz and data was normalised by body weight.

For neuromuscular activation pattern, surface EMG electrodes were placed on the gluteus maximus, biceps femoris, rectus femoris, vastus medialis, and gastrocnemius on both legs and captured at 2000 Hz. A Myon 2.0 system (Vicon, Oxford Metrics, Ltd., UK) and AMBU Blue Sensor 30 × 22 electrodes (Ambu GmbH, Bad Nauheim, Germany) were used. The participants' skin was gently abraded, cleaned, and surface electrodes were placed, following the SENIAM recommendations (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). The signal was rectified, filtered with a low-pass corner frequency of 450 Hz and a high-pass corner frequency of 20 Hz (De Luca, Gilmore, Kuznetsov, & Roy, 2010), and peak normalised.

Variables and definitions

Phases and variables spatially related to the laboratory are depicted in Figure 1. Jump height was calculated via CoM and its vertical velocity at take-off. The difference between the lowest CoM position and CoM position with the participant standing still defined lowering of CoM; normalised to CoM position in a still stance. Approach speed was estimated as horizontal CoM velocity prior to first contact with FP1. Minimal joint angles and maximal angular velocities were received during planting and push-off phase (for ankles, knees, and hips) and all phases (for shoulders). Maximal muscle activation resulted from the peak value during planting and push-off phase; mean activation was derived from the average value over the push-off phase, given as percentage of the maximal activation. Peak values during push-off phase represented maximal joint moments for ankle, knee, and hip extension, normalised to body mass. Maximal vertical forces and rate of vertical force development were defined in the time frame of push-off phase; maximal horizontal forces and horizontal impulses in the time frame of planting phase. The timing of maximal angular velocities and muscle activation was normalised to the total duration of each trial. Striking arm was used as dominant limb.

Statistics

Statistical tests were calculated via PASW Statistics 18.0 (SPSS Inc., Chicago, IL, USA) and Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA). All data were checked for normality and are presented as means ± standard deviation.

Multivariate analysis of variance (MANOVA) was used to calculate differences between sexes in the categories of basic kinematics, minimal joint angles, maximal angular velocities, timing of maximal velocities, maximal joint moments, kinetics, and EMG. Univariate analyses of variance (ANOVA) were applied for differences between sexes in single variables. A mixed ANOVA with repeated-measures (factors: "timing" and "sex") investigated differences in timing of muscle activation and maximal angular velocities between sexes. The levels of "timing" are the different time points when single muscles or joints reached their peak values.

For analyses of variance, effect size was presented as partial eta square ($p\eta^2$). The magnitude was defined as small,

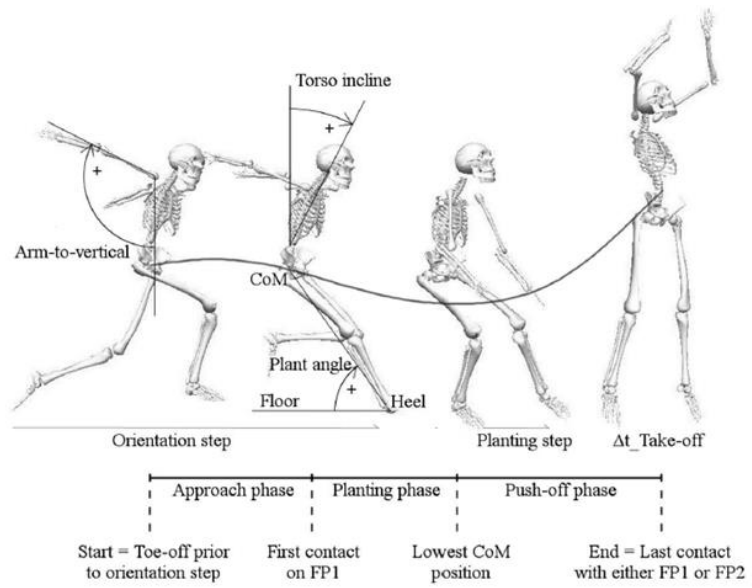


Figure 1. Overall time-frame and definition of phases, terms, and angles relative to the vertical axis.

Note: Approach phase: From last ground contact of the non-dominant foot until first ground contact of the dominant foot during orientation step; Planting phase: From the end of the approach phase until reaching the lowest position of CoM; Push-off phase: From the end of the planting phase until last ground contact at take-off. Plant angle: Angle between CoM, foot-heel, and the projection of CoM on the floor; Δt-Take-off: Time difference between left and right foot take-off (normalised for trial duration).

medium, and large effect using values of .10, .25, and .40, respectively (Cohen, 1992).

Multivariate regression analyses including adjusted R^2 and regression equations were conducted with jump height as criterion, primary variables as predictor, and sex as control variable (male value = 1, female value = 2). Pearson Product Moment correlation coefficient (r) was calculated between jump height and primary variables and among variables representing key biomechanical elements of the performance. The magnitude was defined as small, moderate, and large correlation using values of .1, .3, and .5, respectively (Cohen, 1992). The significance level for all statistical analyses was set a priori at $P< .05$.

Results

MANOVA revealed significant values for basic kinematics, kinetics, maximal joint moments, and mean muscle activation. ANOVA from these groups showed differences in 7 out of 10, 4 out of 11, 4 out of 6, and 5 out of 10 variables, respectively. The main effects of sex revealed via MANOVA and ANOVA are listed in Table 1.

There was an interaction for timing of maximal muscle activation (Figure 2) with sex ($F_{5,128} = 8.25$, $P< .001$, $p\eta^2 = .23$). A main effect for activation timing was found in women ($F_{4,55} = 14.19$, $P< .001$, $p\eta^2 = .50$) and men ($F_{4,51} = 12.89$, $P< .001$, $p\eta^2 = .48$).

The timing of maximal angular velocities did not confirm the interaction with sex ($F_{2,57} = 2.97$, $P= .06$, $p\eta^2 = .01$). A main effect for angular velocity timing in both sexes was found ($F_{2,57} = 452.66$, $P< .001$, $p\eta^2 = .94$). With the exception of the timing of shoulder velocity, all other joints reached their peak between 92% and 96% of total time duration.

All regression models were significant with a range of adjusted R^2 between .71 and .81. Significance of $P< .001$ was observed for the influence of sex on jump height in all derived models. Regression statistics and equations are shown in Figures 3 and 4. Jump height significantly correlated with all primary variables ($|.46| \leq r \leq |.76|$, $P< .05$) except for maximal angular velocity in the dominant shoulder ($r= .29$, $P= .12$). Secondary variables correlated significantly among each other and with related primary variables in 17 out of 24 cases. Pearson's r ranged between .37 and .87 for positive correlation and −.42 and −.84 for negative correlation (Table 2).

Discussion

MANOVA revealed differences between sexes for kinetics and EMG data but not for minimal joint angles and maximal joint velocities. Kinetics and EMG provided helpful insights into the movement patterns and technique of volleyball spike jumps. No differences between sexes could be detected for the timing of maximal angular velocities. The difference in timings of maximal angular velocities across sexes appeared to be due to the differences between lower limbs and shoulders. Excluding the shoulders, all other joints attained their maximal velocity shortly prior to the take-off. This indicates that the timing of maximal joint velocities for the lower extremities is insufficient to detect differences in coordination patterns during the spike jump. In contrast, EMG data revealed that the timing of activation patterns differed between sexes, especially for the dominant leg. These findings were in agreement with Bobbert and van Ingen Schenau (1988) who investigated coordination during vertical jumps in volleyball players. The authors documented no timing differences in maximal hip, knee, and ankle velocities with all peaks around 30 ms before take-off. However, they did report a proximal-to-distal sequence based on the timing of maximal muscular activation. Similar observations were found by Ravn et al. (1999) in volleyball spike jumps. Our data appeared to confirm proximal-to-distal muscle activation for males (gluteus maximus first, gastrocnemius last) but not for females (delayed gluteus maximus, relatively early gastrocnemius activation).

Differences in movements between sexes were found throughout all phases. Surprisingly, vertical impulses were comparable, contrary to the expected differences in jump height (Sattler et al., 2015). This indicates that females exhibited greater vertical movement during the orientation step and generated a hopping movement rather than stepping into the planting phase in comparison to males. The large difference in approach speed showed the importance of including the approach/preparation phase for analyses of jumping motions as recommended by Wagner et al. (2009). The correlation analysis underlined the influence of approach speed on jump height. However, in the regression model accounting for sex, the independent contribution of approach speed was not significant. Correlation results support that differences in approach speed may have also affected other variables. With higher approach speed, males had a longer orientation step and smaller plant angle, meaning they placed the dominant heel further forward on the ground when planting their foot. This allows for stopping their high horizontal velocity more efficiently with the dominant leg in the beginning of the planting phase (instead of the less efficient strategy to achieve velocity transfer with the non-dominant leg, transitioning into push-off phase).

The different roles of both legs in stopping and transferring horizontal velocity are a major finding of this study as well as other studies that hypothesised different mechanics in spike jumps between sexes. Hsieh and Christiansen (2010) indicated that in females, the approach may be used to maximise muscle function rather than to increase horizontal velocity as it is common in males. As shown by the higher horizontal impulse on FP2 compared with FP1, the main responsibility for velocity transfer lies clearly in the non-dominant leg as reported by Wagner et al. (2009). However, the dominant leg of males contributed more profoundly to velocity transfer through an efficient plant angle, thus retaining more power for vertical acceleration in the non-dominant leg ($r= -.67$). Correlation calculations suggest that a smaller plant angle allowed males to create a higher horizontal force peak ($r= -.72$) and impulse ($r= -.84$) with the dominant leg on FP1, while they were comparable on FP2 between women and men. Instead, females increased the length of the planting step to compensate the reduced velocity transfer from the dominant leg. A longer planting step, however, leads to less beneficial angles of the legs in relationship to the ground since feet should be positioned well underneath the hips instead of further apart. Despite positioning, simultaneous take-off of non-dominant and dominant feet is beneficial and tends to be more

Table 1. MANOVA and ANOVA results for females and males. Values are mean ± SD.

Variable	Females	Males	P	pη²
Basic kinematics (MANOVA)			< .001	.91
Jump height [m]	0.37 ± 0.08	0.64 ± 0.09	< .001	.73
Orientation step length [m]	1.18 ± 0.16	1.52 ± 0.20	< .001	.49
Planting step length [m]	0.63 ± 0.12	0.24 ± 0.11	< .05	.15
Minimal CoM position [%]	21 ± 0	24 ± 0	< .05	.21
Plant angle [°]	75 ± 4	67 ± 3	< .001	.53
Approach speed [m·s^{-1}]	2.88 ± 0.34	3.75 ± 0.38	< .001	.61
Torso incline angle [°]	33 ± 6	38 ± 4	< .05	.20
Non-dominant arm-to-vertical angle [°]	-111 ± 16	-114 ± 14	.48	.02
Dominant arm-to-vertical angle [°]	-107 ± 33	-115 ± 14	.37	.03
Relative time difference in take-off FP1-FP2 [%]	2.28 ± 1.16	1.59 ± 1.04	.10	.10
Minimal joint angles (MANOVA)			.10	.35
Non-dominant ankle flexion [°]	87 ± 7	89 ± 9	.39	.03
Dominant ankle flexion [°]	69 ± 3	71 ± 4	.12	.09
Non-dominant knee flexion [°]	121 ± 6	116 ± 7	.09	.10
Dominant knee flexion [°]	96 ± 6	90 ± 4	< .05	.21
Non-dominant hip flexion [°]	117 ± 13	108 ± 9	< .05	.14
Dominant hip flexion [°]	108 ± 11	97 ± 7	< .01	.26
Non-dominant shoulder hyperextension [°]	-89 ± 18	-82 ± 14	.24	.05
Dominant shoulder hyperextension [°]	-96 ± 18	-87 ± 17	.16	.07
Maximal angular velocities (MANOVA)			.11	.34
Non-dominant ankle extension [°·s^{-1}]	686 ± 105	691 ± 106	.90	.00
Dominant ankle extension [°·s^{-1}]	763 ± 165	794 ± 125	.56	.01
Non-dominant knee extension [°·s^{-1}]	677 ± 412	757 ± 79	< .05	.16
Dominant knee extension [°·s^{-1}]	778 ± 135	884 ± 61	< .05	.22
Non-dominant hip extension [°·s^{-1}]	557 ± 95	643 ± 74	< .05	.22
Dominant hip extension [°·s^{-1}]	591 ± 82	669 ± 86	< .05	.19
Non-dominant shoulder flexion [°·s^{-1}]	810 ± 91	925 ± 122	< .01	.23
Dominant shoulder flexion [°·s^{-1}]	830 ± 74	880 ± 78	.08	.10
Timing of maximal angular velocities (MANOVA)			.17	.07
Non-dominant ankle extension [%]	95.4 ± 0.9	94.6 ± 0.8	< .05	.21
Dominant ankle extension [%]	92.9 ± 1.8	93.8 ± 1.3	.15	.07
Non-dominant knee extension [%]	94.4 ± 0.9	92.8 ± 1.2	< .001	.38
Dominant knee extension [%]	92.5 ± 1.8	92.6 ± 1.4	.89	.00
Non-dominant hip extension [%]	94.2 ± 1.7	92.3 ± 3.6	.08	.10
Dominant hip extension [%]	93.1 ± 1.8	93.6 ± 1.6	.45	.02
Non-dominant shoulder flexion [%]	62.7 ± 8.8	63.3 ± 6.4	.810	.00
Dominant shoulder flexion [%]	64.0 ± 9.2	57.6 ± 5.3	< .05	.16
Maximal joint momentum (MANOVA)			< .001	.93
Non-dominant ankle extension [N·m·kg^{-1}]	0.032 ± 0.001	0.027 ± 0.003	< .001	.48
Dominant ankle extension [N·m·kg^{-1}]	0.038 ± 0.001	0.037 ± 0.001	< .001	.39
Non-dominant knee extension [N·m·kg^{-1}]	1.182 ± 0.060	1.144 ± 0.246	.56	.01
Dominant knee extension [N·m·kg^{-1}]	0.413 ± 0.044	0.527 ± 0.038	< .001	.68
Non-dominant hip extension [N·m·kg^{-1}]	0.277 ± 0.119	0.426 ± 0.161	< .01	.23
Dominant hip extension [N·m·kg^{-1}]	0.376 ± 0.074	0.346 ± 0.015	.13	.08
Mean muscle activation (MANOVA)			< .05	.91
Non-dominant gastrocnemius [%]	54 ± 9	61 ± 7	< .05	.17
Dominant gastrocnemius [%]	39 ± 9	41 ± 4	.47	.02
Non-dominant vastus medialis [%]	50 ± 7	54 ± 5	.13	.08
Dominant vastus medialis [%]	39 ± 9	49 ± 4	< .001	.37
Non-dominant rectus femoris [%]	49 ± 5	52 ± 8	.22	.05
Dominant rectus femoris [%]	36 ± 6	49 ± 3	< .001	.69
Non-dominant biceps femoris [%]	45 ± 4	39 ± 10	.05	.13
Dominant biceps femoris [%]	40 ± 6	34 ± 9	< .05	.14
Non-dominant gluteus maximus [%]	41 ± 8	50 ± 10	< .05	.19
Dominant gluteus maximus [%]	39 ± 9	42 ± 10	.38	.03
Kinetics (MANOVA)			< .001	.75
Maximal vertical force (FP1) [N·kg^{-1}]	13.89 ± 1.85	13.95 ± 4.18	.96	.00
Maximal vertical force (FP2) [N·kg^{-1}]	19.60 ± 3.79	20.42 ± 6.51	.68	.01
Difference in maximal vertical force (FP1-FP2) [N·kg^{-1}]	5.71 ± 3.91	6.47 ± 3.69	.60	.01
Maximal horizontal force (FP1) [N·kg^{-1}]	4.76 ± 1.45	6.83 ± 2.72	< .05	.20
Maximal horizontal force (FP2) [N·kg^{-1}]	10.83 ± 3.01	10.66 ± 3.71	.89	.00
Horizontal impulse (FP1) [N·kg^{-1}·s]	0.76 ± 0.15	0.97 ± 0.33	< .05	.14
Horizontal impulse (FP2) [N·kg^{-1}·s]	1.31 ± 0.32	1.32 ± 0.46	.97	.00
Vertical impulse (FP1) [N·kg^{-1}·s]	4.35 ± 0.34	4.51 ± 0.53	.33	.03
Vertical impulse (FP2) [N·kg^{-1}·s]	2.95 ± 0.69	3.18 ± 1.12	.51	.02
Maximal vertical rate of force development (FP1) [N·kg^{-1}·s^{-1}]	28 ± 14	76 ± 42	< .001	.39
Maximal vertical rate of force development (FP2) [N·kg^{-1}·s^{-1}]	595 ± 176	1251 ± 465	< .001	.49

Torso incline angle: 0 = vertical upright position, positive value means forwards incline; arm-to-vertical angle: 0 = vertical downward position, negative value means backswing; relative time difference in take-off FP1-FP2: Expressed as positive values; shoulder hyperextension: 0 = arms and torso with identical orientation in sagittal plane, negative values means backswing of arms relative to torso; FP1 = force plate 1; FP2 = force plate 2.

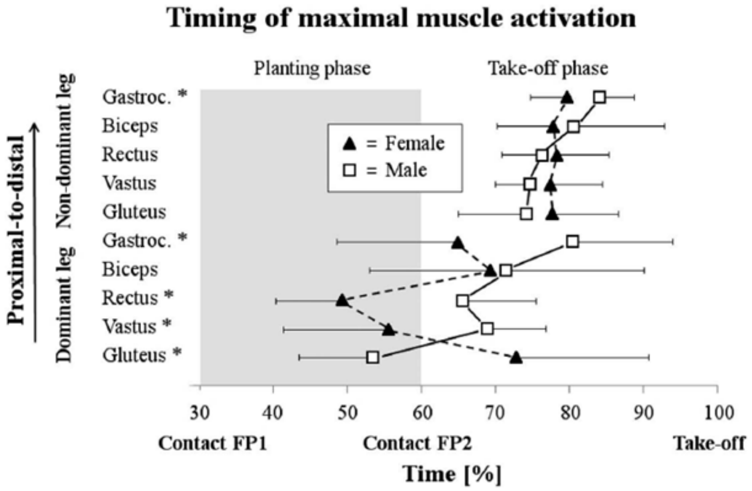


Figure 2. Mean female and male values for maximal muscle activation of lower extremity muscles of the dominant and non-dominant side.

Note: Differences ($P< .05$) between sexes are marked with * at the end of named muscle. FP1 = force plate 1 (contact with dominant leg); FP2 = force plate 2 (contact with non-dominant leg).The muscles are aligned in the order as reported by Bobbert and van Ingen Schenau (1988) to represent a proper activation pattern in skilled jumpers, i.e., proximal-to-distal order.

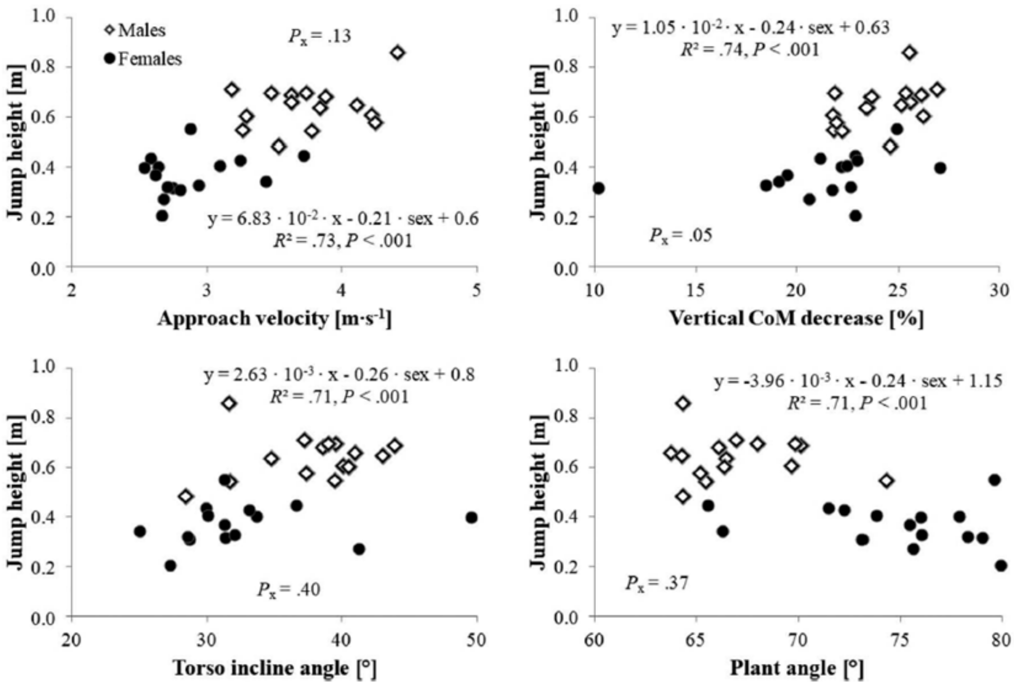


Figure 3. Multivariate regression analyses between jump height and approach velocity, vertical CoM decrease, torso incline, and plant angle, including sex as control variable.

Note: CoM = centre of mass. P_x = Significance value for the influence of the variable on the x-axis on jump height in the derived regression model.

successfully achieved by males. Furthermore, the difference in mean muscle activation supports the idea of a different role and usage of the dominant leg. Four out of five results for activation timing differences between sexes occurred in the dominant leg; only one out of five was significant in the non-dominant leg. This and the largest of maximal joint moment differences found in the dominant knee indicate that especially the dominant leg was used differently. Considering the major differences in approach speed and the horizontal forces on FP1, these differences in dominant leg activation timing could be the result of differences in approach speed. This was supported by the significant correlation between approach speed and four out of five activation timings in the dominant leg. The results suggest that the approach speed may be limited by proper activation timing in the dominant leg. Possible strength or power deficits in females cannot explain a shorter orientation step and thus larger plant

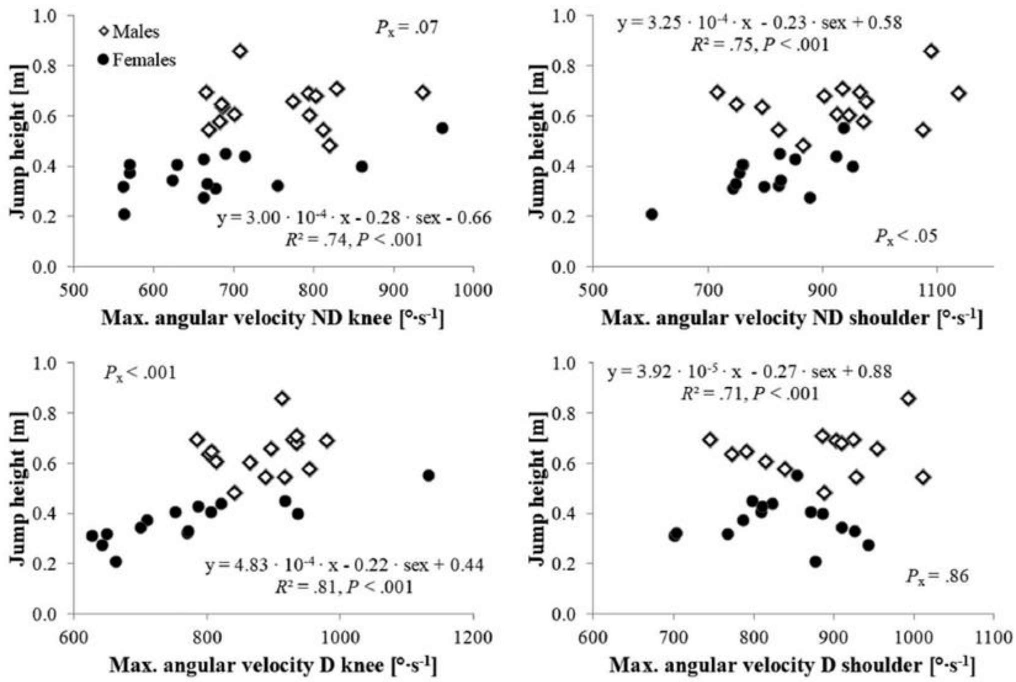


Figure 4. Multivariate regression analyses between jump height and maximal angular velocity of dominant and non-dominant knees and shoulders, including sex as control variable.

Note: D = dominant; ND = non-dominant. P_x = Significance value for the influence of the variable on the x-axis on jump height in the derived regression model.

Table 2. Correlation of secondary variables. The selection includes variables related to biomechanical key aspects for the performance: approach, velocity transfer, upper body lean and arm swing.

Variable 1	Variable 2	r	P
Approach speed	Orientation step length	.87	< .001
Approach speed	Planting step length	.08	.67
Approach speed	Plant angle	-.82	< .001
Approach speed	Timing D gastrocnemius activation	.52	< .01
Approach speed	Timing D vastus lateralis activation	.37	< .05
Approach speed	Timing D rectus femoris activation	.48	< .01
Approach speed	Timing D biceps femoris activation	.15	.42
Approach speed	Timing D gluteus maximus activation	-.52	< .01
Orientation step length	Maximal horizontal force (FP1)	.78	< .001
Orientation step length	Maximal horizontal force (FP2)	.52	< .01
Orientation step length	Horizontal impulse (FP1)	.77	< .001
Orientation step length	Horizontal impulse (FP2)	.36	.05
Plant angle	Maximal horizontal force (FP1)	-.72	< .001
Plant angle	Maximal horizontal force (FP2)	-.42	< .05
Plant angle	Horizontal impulse (FP1)	-.84	< .001
Plant angle	Horizontal impulse (FP2)	-.32	.09
Plant angle	Maximal vertical RFD (FP1)	-.59	< .01
Plant angle	Maximal vertical RFD (FP2)	-.67	< .001
* Upper body incline angle	ND arm-to-vertical angle	-.79	< .001
* Upper body incline angle	D arm-to-vertical angle	-.21	.27
Upper body incline angle	Maximal ND shoulder velocity	.38	< .05
Upper body incline angle	Maximal D shoulder velocity	.17	.37
ND arm-to-vertical angle	Maximal ND shoulder velocity	-.62	< .001
D arm-to-vertical angle	Maximal D shoulder velocity	-.02	.91

FP1 = force plate 1; FP2 = force plate 2; D = dominant; ND = non-dominant; RFD = rate of force development; *partial correlation with shoulder angle as control variable.

angle, which decreases the efficiency of velocity transfer. Undoubtedly, proper activation timing and a simultaneous take-off of both feet are not limited by strength or power but rather enhance power output and jump height, respectively.

When designing training for athletes to improve the dynamics of the approach, the whole phenomenon of velocity transfer should be strongly considered. Otherwise, attempts to increase approach speed may result in detrimental biomechanical conditions for the actual jump (e.g., wider foot position) or may not allow the athlete to transfer the speed efficiently (resulting in greater horizontal vs. vertical jump displacement).

Due to less maximal bending at the knees and hips as well as reduced trunk flexion, females did not reach the same vertical lowering of CoM (in agreement with Walsh et al., 2007). Higher CoM prior to upward acceleration results in a shorter acceleration distance, negatively correlating with jump height (Wagner et al., 2009). Lower CoM and smaller minimum joint angles indicate longer acceleration distance, which is beneficial for jump height as long as muscle contraction is capable of generating the required impulse at the given joint angles. It is worth mentioning that further upper body incline by itself does not affect the knee or the hip angles (since bending the lower spine also leads to upper body lean) but can contribute to lower CoM. Thus, males increased the acceleration distance of CoM through upper body incline without decreasing knee and hip angles to less efficient extend. Additionally, males had smaller minimal angles in hips and the dominant knee. Whether females were limited in their ability to decrease knee and hip angles due to a deficit in power or other factors is unclear. If a strength deficit is considered as main reason for a weak countermovement in individuals, such athletes should employ more strength training of lower limb extension, engaging small joint angles (e.g., full squats) (Hartmann et al., 2012).

It appears that males benefited from the larger torso incline generated during the backswing of the arms. Although the angle between arms and upper body tended to be smaller in males perhaps due to reduced flexibility, overall, males tended to pull back the arms higher relative to the global vertical axis. Correlation supported, this may have been due to further lowering of the upper body. For the non-dominant arm, the positive correlation between upper body incline and shoulder velocity contributed to this occurrence. In fact, males had higher angular velocity in the non-dominant arm but not in the dominant arm. In agreement with Wagner et al. (2009) and Fuchs et al. (2019), only non-dominant arm swing velocity correlated with jump height. In addition, only the influence of the non-dominant arm swing velocity, independent on sex, was significant in the regression models. These findings can be explained via the non-dominant arm being used fully for acceleration and momentum transfer whereas the dominant arm needs to prepare for the strike movement at the push-off phase depending on the specific spike technique (Seminati, Marzari, Vacondio, & Minetti, 2015). It is worth mentioning that increasing arm velocity through upper body momentum is not based on strength in the shoulder joint but due to coordination between arms and upper body. Proper arm swing enables earlier and faster extension of a previously further bent upper body and, thus, generates greater power (Lees et al., 2004). Hence, training should implement improved usage of trunk flexion and arm swing to enhance the overall motion and to facilitate the countermovement. This can be achieved by bringing the chest lower towards the floor and maximising the backswing and velocity of the arms.

Strength and power undoubtedly contribute to jump performance (Sheppard et al., 2008) and muscle morphology and power differ between females and males (Alegre, Lara, Elvira, & Aguado, 2009). In the current sample, there is high probability that sex differences contributed to power. This was revealed through higher maximal rate of force development and angular velocities in males. However, this study demonstrated that strength alone does not cause different performance characteristics. Since technical aspects may be limited by strength, determining an exact distinction of differences caused by strength or technique is challenging. The required power capacity may be able to increase approach velocity, arm swing and upper body lean; but such adaptations may affect overall dynamics of the movement and thus overextend power abilities of muscles around adjacent joints. For instance, females may have the power to increase upper body lean and allow for the subsequent adjustment to body posture that may contribute to ground forces that hinder upward acceleration of the CoM due to power deficit in lower limb extension. However, it can be expected that factors such as muscular activation timing and time discrepancy of left and right foot take-off are not limited by strength and power deficits but can contribute to improve the power output and jump height.

Correlation analyses revealed that primary variables affect jump height. However, multivariate regression analyses indicated that the influence of some primary variables may be sex-related and that sex should be accounted for. Comparing sex-specific studies (Fuchs et al., 2019; Wagner et al., 2009), some characteristics related to jump height in both sexes (e.g., countermovement, dominant arm swing). However, correlation of other factors (e.g., horizontal-to-vertical velocity conversion) is documented only in females. Independent of sex, primary variables seem reasonable to be targeted and integrated in jump performance training for any athlete exhibiting the corresponding technical-coordinative weaknesses.

As the number of setters and libero (whose main task is not the execution of spike jumps) was comparable between both teams, an influence on the group comparison was not expected.

Conclusion

Major findings in this study include the application of an increased approach speed, more dynamic arm swing including upper body lean, and greater lowering of CoM in males compared to females during the volleyball spike jump. All of these variables affect jump height. Ground reaction forces suggest greater power in males, while kinematics and especially EMG data revealed males and females employ different strategies to capitalise on approach speed through the planting angle and muscular activation patterns in the dominant leg. For a holistic approach to understanding technique in complex jumping movements, we recommend that future studies do not rely only on kinematics but also consider EMG and kinetic data.

The current results contribute to the understanding of sex-specific technical-coordinative characteristics of the volleyball spike jump and can be used to adapt to jump training. Differences in motion characteristics do not automatically mean that the females' characteristics are negative only because females' jump height is lower; these may be due to sex-specific optimum technique and coordination. Most studies defining proper technique or coordination investigated only males. An upcoming investigation will evaluate the sex-specific effect of the currently analysed variables on the performance of the volleyball spike jump.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

No funding and grant-awarding to be declared.

ORCID

Philip X. Fuchs http://orcid.org/0000-0002-7463-8301
Hans-Joachim Karl Menzel http://orcid.org/0000-0001-7448-9636

References

Alegre, L., Lara, A., Elvira, J., & Aguado, X. (2009). Muscle morphology and jump performance: Gender and intermuscular variability. *Journal of Sports Medicine and Physical Fitness*, *49*(3), 320–326.

Bobbert, M. F., & van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal of Biomechanics*, *21*(3), 249–262.

Bruton, M. R., O'Dwyer, N., & Adams, R. (2013). Sex differences in the kinematics and neuromuscular control of landing: Biological, environmental and sociocultural factors. *Journal of Electromyography and Kinesiology*, *23*(4), 747–758.

Chen, P., Huang, C., & Shih, S. (2011). *Differences in 3D kinematics between genders during volleyball spike*. Paper presented at the Proceedings of the Congress of the International Society of Biomechanics. Brussels: Belgium.

Chiu, M.-C., & Wang, M.-J. (2007). The effect of gait speed and gender on perceived exertion, muscle activity, joint motion of lower extremity, ground reaction force and heart rate during normal walking. *Gait & Posture*, *25*(3), 385–392.

Chu, Y., Fleisig, G. S., Simpson, K. J., & Andrews, J. R. (2009). Biomechanical comparison between elite female and male baseball pitchers. *Journal of Applied Biomechanics*, *25*(1), 22–31.

Chumanov, E. S., Wall-Scheffler, C., & Heiderscheit, B. C. (2008). Gender differences in walking and running on level and inclined surfaces. *Clinical Biomechanics*, *23*(10), 1260–1268.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155–159.

De Luca, C. J., Gilmore, L. D., Kuznetsov, M., & Roy, S. H. (2010). Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal of Biomechanics*, *43*(8), 1573–1579.

Dempster, W. T. (1955). *Space requirements of the seated operator, geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs* (pp. 55–159). Dayton, OH: Wright-Patterson Air Force Base.

Drikos, S., Kountouris, P., Laios, A., & Laios, Y. (2009). Correlates of team performance in volleyball. *International Journal of Performance Analysis in Sport*, *9*(2), 149–156.

Ferber, R., Davis, I. M., & Williams, D. S., III. (2003). Gender differences in lower extremity mechanics during running. *Clinical Biomechanics*, *18*(4), 350–357.

FIVB.(2016). FIVB volleyball world rankings. Retrieved from http://www.fivb.org/en/volleyball/Rankings.asp

Fuchs, P. X., Fusco, A., Bell, J. W., von Duvillard, S. P., Cortis, C., & Wagner, H. (2019). Movement characteristics of volleyball spike jump performance in females. *Journal of Science and Medicine in Sport*, *22*, 833–837.

Hanavan, E. (1964). *A mathematical model for the human body*. Dayton, OH: Wright-Patterson Air Force Base.

Hartmann, H., Wirth, K., Klusemann, M., Dalic, J., Matuschek, C., & Schmidtbleiber, D. (2012). Influence of squatting depth on jumping performance. *The Journal of Strength & Conditioning Research*, *26*(12), 3243–3261.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *10* (5), 361–374.

Hsieh, C., & Christiansen, C. L. (2010). The effect of approach on spike jump height for female volleyball players. *International Journal of Sports Science & Coaching*, *5*(3), 373–380.

Kerrigan, D. C., Todd, M. K., & Croce, U. D. (1998). Gender differences in joint biomechanics during walking normative study in young adults. *American Journal of Physical Medicine & Rehabilitation*, *77*(1), 2–7.

Laffaye, G., Wagner, P. P., & Tombleson, T. I. (2014). Countermovement jump height: Gender and sport-specific differences in the force-time variables. *The Journal of Strength & Conditioning Research*, *28*(4), 1096–1105.

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics*, *37*(12), 1929–1940.

Liu, H., Leigh, S., & Yu, B. (2009). *Upper extremity motion sequence in javelin throwing*. Paper presented at the Proceedings of the Congress of the 33rd American Society of Biomechanics. University Park, PA.

Ravn, S., Voigt, M., Simonsen, E. B., Alkjaer, T., Bojsen-Møller, F., & Klausen, K. (1999). Choice of jumping strategy in two standard jumps, squat and countermovement jump-effect of training background or inherited preference? *Scandinavian Journal of Medicine & Science in Sports.*, *9*(4), 201–208.

Sattler, T., Hadžic, V., Derviševic, E., & Markovic, G. (2015). Vertical jump performance of professional male and female volleyball players: Effects of playing position and competition level. *The Journal of Strength & Conditioning Research*, *29*(6), 1486–1493.

Selbie, W. S., Hamill, J., & Kepple, T. M. (2013). Three-dimensional kinetics. In G. Robertson, G. Caldwell, J. Hamill, & S. Whittlesey (Eds.), *Research methods in biomechanics* (pp. 151–176). Champaign, IL: Human Kinetics.

Seminati, E., Marzari, A., Vacondio, O., & Minetti, A. E. (2015). Shoulder 3D range of motion and humerus rotation in two volleyball spike techniques: Injury prevention and performance. *Sports Biomechanics*, *14*(2), 216–231.

Sheppard, J. M., Cronin, J. B., Gabbett, T. J., McGuigan, M. R., Etxebarria, N., & Newton, R. U. (2008). Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *The Journal of Strength & Conditioning Research*, *22*(3), 758–765.

Viera, B. L., & Ferguson, B. J. (1989). *Teaching volleyball. steps to success*. Champaign, IL: Leisure Press.

Wagner, H., Tilp, M., von Duvillard, S. P., & Müller, E. (2009). Kinematic analysis of volleyball spike jump. *International Journal of Sports Medicine*, *30*(10), 760.

Waite, P. (2009). *Aggressive volleyball*. Champaign, IL: Human Kinetics.

Walsh, M. S., Böhm, H., Butterfield, M. M., & Santhosam, J. (2007). Gender bias in the effects of arms and countermovement on jumping performance. *The Journal of Strength & Conditioning Research*, *21*(2), 362–366.

Woltring, H. J. (1986). A Fortran package for generalized, cross-validatory spline smoothing and differentiation. *Advances in Engineering Software (1978)*, *8*(2), 104–113.

Ziv, G., & Lidor, R. (2010). Vertical jump in female and male volleyball players: A review of observational and experimental studies. *Scandinavian Journal of Medicine & Science in Sports*, *20*(4), 556–567.

ARTICLE 2

Fuchs, P. X., Fusco, A., Bell, J. W., von Duvillard, S. P., Cortis, C., & Wagner, H. (2019).

Movement characteristics of volleyball spike jump performance in females.

Journal of Science and Medicine in Sport, 22(7), 833-837.

Impact Factor (2018): 3.623

Journal of Science and Medicine in Sport 22 (2019) 833–837

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

JSAMS
Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

ELSEVIER

Original research

Movement characteristics of volleyball spike jump performance in females

Philip X. Fuchs[a,b,*], Andrea Fusco[a,b], Jeffrey W. Bell[c], Serge P. von Duvillard[a], Cristina Cortis[b], Herbert Wagner[a]

[a] Department of Sport Science and Kinesiology, University of Salzburg, Salzburg, Austria
[b] Department of Human Sciences, Society and Health, University of Cassino and Lazio Meridionale, Cassino, Italy
[c] Science Department, Southwest Minnesota State University, Marshall, Minnesota, USA

ARTICLE INFO

Article history:
Received 4 September 2018
Received in revised form
10 December 2018
Accepted 1 January 2019
Available online 6 January 2019

Keywords:
Jump height
Ball velocity
Influence
Kinematic
Specific training

ABSTRACT

Objectives: Performance factors in the volleyball spike jump are well known for male players; however, technical-coordinative differences for female players are known only marginally. The objective of this study was to investigate the relationship between movement characteristics and female' spike jump performance and to identify the most relevant aspects of jump height and ball velocity.
Design: Single group correlation and regression.
Methods: Fifteen elite female volleyball players performed spike jumps by striking a stationary ball at maximal jump height. Data were collected via twelve MX13 Vicon cameras (250 Hz), two AMTI force plates (2000 Hz), and controlled via Visual3D software.
Results: Ten out of 42 characteristics correlated with jump height and none of 22 correlated with ball velocity. A stepwise regression model (adjusted $R^2 = 0.82$, $p < 0.001$) predicted jump height based on orientation step length and maximal angular velocity of dominant knee extension. For ball velocity, stepwise regression analysis was not feasible; however, an alternative model yielded adjusted $R^2 = 0.55$, $p < 0.01$.
Conclusions: Key aspects for jump height were (1) optimised approach and energy conversion, (2) wide dynamic arm swing allowing for a forceful countermovement and, thus, increased range of motion in lower limbs, and (3) large angular velocities in ankles and knees, especially on the dominant side. These aspects strongly determined jump height in females and should be included in technical and strength-related training. For ball velocity, upper body anthropometrics and angular joint velocities emerged as the most important criteria. The importance of specific joints may depend on variations in striking technique.

Practical implications

- Enhance explosiveness through a large lower limb range of motion in jumping.
- Optimise approach speed and improve horizontal-to-vertical velocity conversion.
- Encourage wide and dynamic arm swing to enhance countermovment and a powerful push-off.

1. Introduction

Volleyball is an Olympic sport wherein athletes perform multiple technically complex movements. In offensive play, a spike is the most effective attack play associated with success in matches.[1] Players attempt to reach a great jump height when spiking (1) to increase possibilities for various different types of actions and (2) to maximise the effective court size, allowing for a steep ball trajectory at great ball velocity. Two of the main performance determinants for the spike are jump height and ball velocity; previous studies found correlations between these factors and overall competition level in volleyball.[2,3] Therefore, jump height and spike velocity are major factors in volleyball training[4] and competition.

Due to the specificity and complexity of the volleyball spike, it is imperative to possess not only strength and power but also

* Corresponding author at: Department of Sport Science and Kinesiology, University of Salzburg, Rifer Schlossallee 49, 5400 Hallein/Rif, Austria.
E-mail address: philip.fuchs@sbg.ac.at (P.X. Fuchs).

https://doi.org/10.1016/j.jsams.2019.01.002
1440-2440/

technical and coordinative aspects that contribute to performance. According to theoretical descriptions,[5–7] the volleyball spike jump should be introduced with a horizontal approach that assists in transferring the body into vertical acceleration. Swinging the arm with maximal range of motion promotes increased momentum and ground reaction forces. A countermovement is performed via upper body lean and the decrease of lower limb angles. This pre-activates lower limb muscles, initiates a stretch-shortening-cycle, and optimises the distance of acceleration. Subsequently, a dynamic arm swing, elevation of upper body, and extension in the hips, knees, and ankles establish an explosive push-off. During the end of push-off, pelvis rotation generates momentum that is transferred during the flight phase via trunk rotation and flexion into fast shoulder and elbow movements to spike the ball at maximal speed.

Experimental studies on optimal jump mechanics have been conducted mainly with male participants. They highlighted the relevance of ground reaction forces[8] and approach speed, depth of the countermovement, knee angles, and arm swing.[9] For spike velocity, the generation of momentum in the pelvis and torso and the transition into great angular velocities in the shoulder internal rotation and flexion and elbow extension are known and essential.[10] There are few reports for females' performance, but the same performance characteristics are assumed equally important. Limited findings indicate that the key characteristics before take-off (i.e. approach speed, countermovement, and arm swing) may contribute to jump height[11–14] and ball velocity.[12] However, technical differences between women and men,[14–16] particularly in the aforementioned key characteristics,[17] suggest that technical aspects may not have the same effect on performance in females as in males. Knowledge of performance factors in females is lacking but represents the basic prerequisite to optimise specific training.

The objective of the current study was (1) to investigate the relationship of biological, training historical, kinematic, and kinetic data with jump height and ball velocity in females' volleyball spike jumps, and (2) to identify the key indicators determining females' jump height and spike velocity. A sufficient number of correlations to reliably ($R^2 > 0.7$) predict jump height and ball velocity was hypothesised.

2. Methods

A female elite volleyball team ($n = 15$) from the highest national division in Austria participated in the current study (age: 19.9 ± 3.5 years, body height: 1.79 ± 0.06 m, body mass: 70.47 ± 11.02 kg, reach height: 2.28 ± 0.08 m, training experience: 8.4 ± 3.9 years, training hours per week: 11.5 ± 2.2 h). In agreement with the Declaration of Helsinki, the local research ethics committee approved the investigation. All players were injury-free and physically healthy at the time of data collection and signed the informed consent after review.

After a general warm-up (e.g. running, jumping, arm movements), the athletes performed multiple test trials for specific warm-up, familiarisation, localisation of the optimal position of the ball hanging stationary from the ceiling at the self-selected individual optimal approach distance and angle. A valid spike jump fulfilled the following requirements: (1) Both players' feet must have contacted the two force plates on the ground separately; (2) both, the player and coach, agreed that a maximal jump height and powerful strike were achieved. Instructions were to not focus on the force plates but instead on jump height and spike velocity. Trials were repeated until 10 valid spike jumps were recorded. To avoid fatigue, athletes were free to take a one-minute break between trials. The overall movement is shown in Fig. 1, including definitions of various phases and terms.

Measured at a frequency of 250 Hz, 51 reflective markers (14 mm diameter) were captured by twelve Vicon MX-13 cameras (Vicon, Oxford Metrics, Ltd., UK). A Cleveland Clinical Marker set (Motion Analysis Corp, Santa Rosa, USA) was used with marker clusters at the legs.[18] Data handling and filtering according to Woltring[19] were conducted in the Nexus 1.8. software (Vicon, Oxford Metrics, Ltd., UK). Segmental movements were calculated and analysed via Visual3D software (C-Motion, Inc., Rockville, MD). Visual3D calculates the centre of body mass (CoM) based on segment positions and regression equations from Dempster.[20]

The z-axis was aligned vertically; the perpendicular x- and y-axes represented the horizontal floor. Ankle, knee, hip, shoulder, and elbow extension were defined as change of sagittal angle between foot and shank, shank and thigh, thigh and torso, upper arm and torso, and upper arm and forearm, respectively. Torso flexion was calculated on the sagittal plane relative to the pelvis segment. Pelvis, torso, and shoulder rotation were derived from the segments' longitudinal change of angle.

Two separate AMTI force plates (AMTI, Watertown, MA) obtained ground reaction data at 2000 Hz. The plates (120×60 cm) were aligned next to each other to allow participants to hit one force plate with the rear leg (FPR), the other force plate with the front leg (FPF). A fourth-order low-pass Butterworth filter at 50 Hz and data normalisation to body mass were applied.

Age, training hours per week, total number of training years, body height, body mass, reach height, leg, upper arm and forearm length of each athlete were collected by one experienced researcher prior to the testing. The dominancy of legs and arms was defined by the spiking arm.

CoM and its vertical take-off velocity were used for jump height calculation. The countermovement (lowering of CoM) was derived from the difference between lowest CoM position during the trial and CoM position in still stance, normalised to CoM position in still stance. Horizontal CoM velocity at first contact with FPR defined approach speed. Relevant for jump height, range of motion (RoM) and maximal angular velocities were computed for ankles, knees, and hips extension during planting and push-off phase and for shoulder flexion from approach to take-off. Ball velocity was defined as the maximal velocity of the centre of the ball, which was calculated via two opposing markers on the ball surface. Relevant for ball velocity, RoM and maximal angular velocities were computed for pelvis rotation during push-off and flight phase and for torso rotation and flexion, dominant shoulder internal rotation and extension, and elbow extension during flight phase. Maximal vertical forces and rate of vertical force development were obtained during the push-off phase; maximal horizontal forces and horizontal impulses during the planting phase.

Data were managed using Microsoft Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA) and statistical analysis was conducted via PASW Statistics 18.0 (SPSS Inc., Chicago, IL, USA). Normality of distribution was determined based on the Shapiro-Wilk test, skewness, and kurtosis. Pearson's Product Moment correlation and two separate forward-stepwise linear regression analyses for the two criterion variables (jump height, ball velocity) were performed, including only significant correlations. The variables for both distinct analyses were selected on the basis of existing knowledge that supports a relationship between these variables as described in the introduction. In the case of co-linearity, the variable possessing the strongest correlation with the criterion variable remained; the others were excluded prior to the regression analysis. If this resulted in a critically small number of remaining correlations, the regression method "enter" was considered. The significance level for correlation and regression analyses was set a priori at $p < 0.05$.

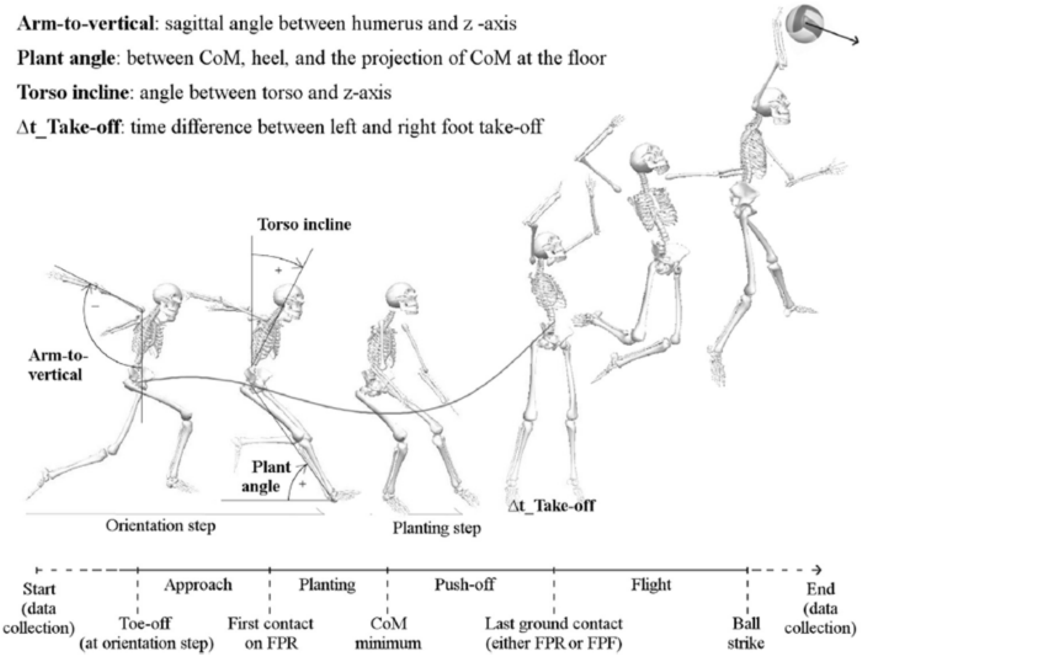


Fig. 1. Time window of analyses, phases, and variables of the volleyball spike jump. Note: FPR/F = force plate hit by rear/front leg; CoM = centre of body mass.

Table 1
Significant correlation results, displaying mean ± standard deviation (SD), 95% confidence intervall (CI), significance level (p), and correlation coefficient (r).

Variables	Mean	±	SD	95% CI			p	r
Orientation step length [m]	1.18	±	0.16	1.09	–	1.26	<0.05	0.61
Min. ND arm-to-vertical angle [°]	111	±	16	102	–	119	<0.05	-0.60
RoM ND ankle [°]	46	±	5	43	–	49	<0.01	0.72
RoM D ankle [°]	59	±	6	55	–	62	<0.01	0.69
RoM D knee [°]	65	±	10	59	–	70	<0.001	0.82
Max. ND ankle velocity [$° s^{-1}$]	686	±	105	628	–	744	<0.01	0.75
Max. D ankle velocity [$° s^{-1}$]	763	±	165	672	–	854	<0.01	0.72
Max. ND knee velocity [$° s^{-1}$]	677	±	112	615	–	739	<0.05	0.59
Max. D knee velocity [$° s^{-1}$]	778	±	135	703	–	852	<0.001	0.85
Max. ND shoulder velocity [$° s^{-1}$]	810	±	91	760	–	861	<0.05	0.64

Note: ND = non-dominant; D = dominant; RoM = range of motion.

3. Results

The supplementary table depicts all variable means ± standard deviations and correlation results with jump height and ball velocity. There was no correlation between jump height and ball velocity ($r = 0.36$, $p = 0.19$). Ten of 42 variables correlated with jump height (Table 1) and none of 22 correlated with ball velocity. Variables that closely missed significance ($0.05 \leq p > 0.10$) should be mentioned for jump height: Age ($r = 0.49$), training years ($r = 0.50$), relative time difference in left to right foot take-off ($r = -0.51$), range of motion in the non-dominant shoulder ($r = 0.49$), and horizontal impulse on FPF ($r = 0.46$); and for ball velocity: Age ($r = 0.52$), upper arm ($r = 0.44$) and forearm length ($r = 0.49$), maximal angular velocity of pelvis rotation ($r = 0.49$) and elbow extension ($r = 0.51$).

For jump height, the final regression model included the maximal angular velocity in the dominant knee extension and the length of the orientation step. It achieved an adjusted $R^2 = 0.82$, $p < 0.001$, and the regression equation was jump height = ($-0.21 + 4.49 \times 10^{-4}$ × maximal dominant knee extension angular velocity + 0.20 × orientation step length).

For ball velocity, no stepwise regression model could be derived due to the lack of significant correlation results. By utilising the variables close to significance ($p < 0.1$) after excluding co-linearity between upper arm and forearm length, a regression model with adjusted $R^2 = 0.55$, $p < 0.01$ was achieved. The equation was ball velocity = ($-6.80 + 51.02$ × forearm length + 1.33×10^{-2} × maximal pelvis rotation angular velocity + 3.33×10^{-3} × maximal elbow extension angular velocity).

4. Discussion

4.1. Jump height

Regression analysis for predicted jump height explains 82% of the criterion's variance with only two predictor variables (i.e. length of the orientation step during approach, maximal angular velocity of the dominant knee extension during push-off). This simple model successfully predicted 82% of the variance in females' spike jump height. The multipliers in the regression equation imply an increase in jump height by 1 cm per $22° s^{-1}$ increase in maximal dominant knee extension angular velocity and 5 cm per prolonged orientation step length. From a practical point of view, the model may have one downside. Determining angular velocity of the knee may be difficult to measure in some environments. The length of the orientation step that resulted in 32% of the variance in this model is less challenging to measure. However, the main goal of the regression analysis was not the prediction but to point out the most influential indicators. The derived model presented very clearly the key variables determining females' spike jump height and highlighted the importance of the orientation step length and dominant knee extension velocity. Both indicator variables strongly interact with other variables and contribute to two complex aspects of jumping (i.e. approach, lower limb power). Therefore, the variables of the model underline key areas for practical training application but their roles need to be assessed in the context of related variables.

The orientation step length interacts with approach velocity and foot planting angle;[17] together, these variables characterise the approach. Increased approach velocity usually results in a longer orientation step. In the current study, approach velocity did not correlate with jump height, contrary to previous reports[9] in males. Also Ikeda et al.[21] found no correlation of jump height with approach velocity in females. Instead, they found a correlation with the deceleration of horizontal CoM velocity during the planting phase. This indicates a less efficient ability to decelerate and convert horizontal speed in some females and suggests its relevance for females.[21] Despite not achieving linear correlation, increased approach speed can be expected to be beneficial as long as successful conversion is warranted. Similarly, an elongated orientation step is only beneficial if it is the result of an increased approach velocity and that is required for successful vertical conversion. However, the difference is that approach velocity is irreversibly defined after the push-off in the beginning of the orientation step and can hamper full conversion; whereas the step length is one of the tools for successful conversion and can be adapted to approach velocity during the orientation step. Therefore, there was higher probability that a participant exceeded her capacity to convert an increased approach speed fully than the participant having applied an orientation step that was too long. This could explain why no linear correlation was observed for approach speed but was observed for orientation step length. Overall, the current findings are in agreement with previously mentioned reports[17,21] that support the relevance of an optimised approach velocity and the ability of successful conversion.

The maximal angular velocities of the knees and ankles on both dominant and non-dominant sides represented a cluster among the correlating variables that can be associated with muscular strength and power development. Angular velocities may be enhanced by technical and coordinative abilities but strength is a decisive aspect. The importance of muscular strength and the ability to generate power explosively through lower limb extension is documented[22,23] and displays its effect in the large number of correlating angular velocities. Especially the dominant knee extension appeared essential,[21] given that its maximal angular velocity revealed the strongest correlation in the current investigation.

Arm swing can promote proximal-to-distal coordination in female volleyball players during countermovement jumps.[24] Furthermore, dynamic arm usage increases the physical power and work in the torso, angular velocities in the lower limbs, and ground reaction forces.[25] Two arm variables characterising the range of backswing and dynamics of the non-dominant arm correlated with jump height. In agreement with previous findings[9,25], this supports the positive effect of the arm swing on jump performance. Correlation was only found on the non-dominant side; the same was observed in another study.[9] The dominant arm may be used less to optimise jump height since it is the striking arm initiating preparative actions for the strike before the take-off.

The importance of the countermovement was not shown through the vertical decrease of CoM but the RoM of the dominant knee and ankles of both sides. In males, Wagner et al.[9] found a correlation with jump height for CoM decrease and for minimal knee angle. Bending the knee benefits the pre-activation and stretch-shortening-cycle and improves the acceleration distance for the joint extension. Furthermore, power in the knee extension is known to be relevant generally for vertical jumps[26] and specifically for decelerating approach velocity in females' volleyball spike jumps.[21] The underestimated importance of the dominant leg in energy conversion was reported[17] and this seems to be supported in females through the present correlation with jump height. Maximal angular velocity and RoM of the dominant knee achieved the strongest correlation coefficients in this study ($r = 0.85$ and 0.82). In comparison, the non-dominant counterpart scored lower for angular velocity ($r = 0.59$) and lacked significance for RoM. Similar to increased approach velocity under certain conditions, decreased CoM can improve jump height only if followed by a powerful push-off. Therefore, strength training especially for the dominant knee extension engaging small joint angles is recommended. This can enhance knee extension power and allow for more pronounced and effective countermovement.

4.2. Ball velocity

Stepwise regression analysis could not be conducted for ball velocity since no significant correlation was found. The alternative model entering the variables with the strongest correlation results ($p < 0.1$) was significant but explained only 55% of the model's variance.

The correlation analysis for upper arm and forearm length just missed significance. Arm length tended to affect ball velocity. A relationship between arm length and ball velocity was previously found in overarm movements[27,28] but not in females' volleyball spike.[29] Thus, a correlation can be reasoned via longer acceleration paths of distal segment parts.

Maximal angular joint velocities in the upper body indicated a role for ball velocity. Pelvis rotation and elbow extension tended to correlate with ball velocity. However, no other trends were found despite the knowledge that internal shoulder rotation is important.[10] The reason could be variation in technique within the sample population, underscored by large standard deviations especially in the internal shoulder rotation. These large standard deviations reduced statistical power. The volleyball spike can be performed in different technical variations; the two most typical ones (i.e. elevations style, backswing style) are associated with different joint kinematics.[30] Explicitly, internal shoulder rotation velocity differs between these striking styles.[30] The variation of striking styles possessing different joint kinematics could have led to weak correlation results between angular joint velocities and ball velocity. Another contribution to the observed technical variability may be that this sample consisted of only one team including all positions. At this stage, it is not possible to assess whether the current results are due to striking technique affecting statistics or due to little relevance of the measured variables. To conduct such assessment, specific differentiation of striking techniques is required.

Jump height did not correlate with ball velocity and should not be viewed as a causal influence on ball velocity. Reported correlation[2,12] may be explained through both variables having a strong causal relationship with skill level. Skill and competition level is well known to be associated with both jump height[3] and spike velocity.[2]

5. Conclusion

A linear regression model predicted jump height successfully ($R^2 = 0.82$) through orientation step length and maximal angular velocity of the dominant knee extension. Jump height correlated with multiple variables that are considered important aspects for the quality of the spike jump movement. These aspects are a dynamic approach, leg extension angular velocities (especially dominant side), non-dominant arm swing, and countermovement. They showed to relate to females' spike jump height and should be addressed in training.

For ball velocity, stepwise regression analysis was not feasible due to the lack of significant correlation results. An alternative model was rather weak ($R^2 = 0.55$). Arm length had the strongest impact on ball velocity, followed by maximal angular velocities in upper body joints. The importance of maximal angular velocities of particular joints may depend on the individually prioritised variation of ball striking technique. This could have been the reason for weak correlation results and striking technique should be considered in future research and practical training.

Acknowledgments

There are no grants, financial support and technical or other assistance to be acknowledged. The authors want to thank the athletes for participating in this study and the coaches for sharing their practical expertise.

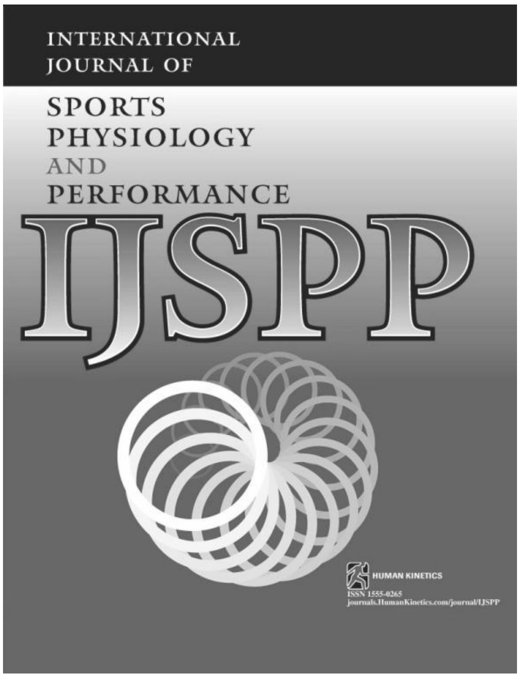
Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jsams.2019.01.002.

References

1. Palao JM, Santos JA, Ureña A. Effect of team level on skill performance in volleyball. *Int J Perf Anal Sport* 2014; 4(2):50–60.
2. Forthomme B, Croisier J-L, Ciccarone G et al. Factors correlated with volleyball spike velocity. *Am J Sport Med* 2005; 33(10):1513–1519.
3. Ziv G, Lidor R. Vertical jump in female and male volleyball players: a review of observational and experimental studies. *Scand J Med Sci Sport* 2010; 20(4):556–567.
4. Powers ME. Vertical jump training for volleyball. *Strength Cond J* 1996; 18(1):18–23.
5. Tilp M. *Biomechanische Aspekte des Volleyballspiels–Sprung, Schlag und Ballflugbahn, 99-113, in Volleyball–europaweit 2003*, Hamburg, Germany, Feldhaus Edition Czwalina, 2004.
6. Waite P. *Aggressive volleyball*, Champaign, IL, Human Kinetics, 2009.
7. Viera BL, Ferguson BJ. *Teaching volleyball. Steps to success*, Champaign, IL, Leisure Press, 1989.
8. Bobbert MF, van Ingen Schenau GJ. Coordination in vertical jumping. *J Biomech* 1988; 21(3):249–262.
9. Wagner H, Tilp M, von Duvillard SP et al. Kinematic analysis of volleyball spike jump. *Int J Sports Med* 2009; 30(10):760–765.
10. Wagner H, Pfusterschmied J, Tilp M et al. Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scand J Med Sci Sport* 2014; 24(2):345–354.
11. Caruso JF, Daily JS, Olson NM et al. Anthropometry and gender influences on the arm swing's contribution to vertical jump heights. *Isokinet Exerc Sci* 2012; 20(1):23–29.
12. Chen Y-C, Huang C-F. Kinematical analysis of female volleyball spike, 617-620. *ISBS-Conference Proceedings Archive* 2008. Available at: https://ojs.ub.uni-konstanz.de/cpa/article/view/1952. [Accessed 3 September 2018].
13. Hsieh C, Christiansen CL. The effect of approach on spike jump height for female volleyball players. *Int J Sports Sci Coaching* 2010; 5(3):373–380.
14. Walsh MS, Böhm H, Butterfield MM et al. Gender bias in the effects of arms and countermovement on jumping performance. *J Strength Cond Res* 2007; 21(2):362–366.
15. Chen P-C, Huang C, Shih S-M. Differences in 3D kinematics between genders during volleyball spike, *Proceedings of the Congress of the International Society of Biomechanics*, 2011,. Available at: https://bit.ly/2wH1SE6. [Accessed 3 September 2018].
16. Sattler T, Hadžic V, Dervišević E et al. Vertical jump performance of professional male and female volleyball players: effects of playing position and competition level. *J Strength Cond Res* 2015; 29(6):1486–1493.
17. Fuchs PX, Menzel H-JK, Guidotti F, Bell J, von Duvillard SP, Wagner H. Sex differences in biomechanical characteristics during volleyball spike jumping. J Sport Sci. [under review].
18. Selbie WS, Hamill J, Kepple TM. Three-dimensional kinetics, 151-176, In: *Research methods in biomechanics*. Champaign, IL, Human Kinetics, 2014.
19. Woltring HJ. A Fortran package for generalized, cross-validatory spline smoothing and differentiation. *Adv Eng Software* 1986; 8(2):104–113.
20. Dempster WT. *Space requirements of the seated operator, geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs*, Dayton, OH, Wright-Patterson Air Force Base, 1955.
21. Ikeda Y, Sasaki Y, Sorimachi S et al. Factors influencing spike jump height in female college volleyball players. *J Strength Cond Res* 2018; 32(1):267–273.
22. Copič N, Dopsaj M, Ivanović J et al. Body composition and muscle strength predictors of jumping performance: differences between elite female volleyball competitors and nontrained individuals. *J Strength Cond Res* 2014; 28(10):2709–2716.
23. Kraska JM, Ramsey MW, Haff GG et al. Relationship between strength characteristics and unweighted and weighted vertical jump height. *Int J Sport Physiol* 2009; 4(4):461–473.
24. Chiu LZ, Bryanton MA, Moolyk AN. Proximal-to-distal sequencing in vertical jumping with and without arm swing. *J Strength Cond Res* 2014; 28(5):1195–1202.
25. Lees A, Vanrenterghem J, De Clercq D. Understanding how an arm swing enhances performance in the vertical jump. *J Biomech* 2004; 37(12):1929–1940.
26. Paasuke M, Ereline J, Gapeyeva H. Knee extension strength and vertical jumping performance in nordic combined athletes. *J Sports Med Phys Fit* 2001; 41(3):354–361.
27. Matsuo T, Escamilla RF, Fleisig GS, et al. Comparison of kinematic and temporal parameters between different pitch velocity groups. *J Appl Biomech* 2001; 17(1):1–13.
28. Van Den Tillaar R, Cabri JM. Gender differences in the kinematics and ball velocity of overarm throwing in elite team handball players. *J Sport Sci* 2012; 30(8):807–813.
29. Ferris DP, Signorile JF, Caruso JF. The relationship between physical and physiological variables and volleyball spiking velocity. *J Strength Cond Res* 1995; 9(1):32–36.
30. Seminati E, Marzari A, Vacondio O et al. Shoulder 3D range of motion and humerus rotation in two volleyball spike techniques: injury prevention and performance. *Sport Biomech* 2015; 14(2):216–231.

ARTICLE 3



Impact Factor (2018): 3.979

Fuchs, P. X., Fusco, A., Bell, J. W., von Duvillard, S. P., Cortis, C., & Wagner, H. (accepted).

The effect of Differential Training on female volleyball spike jump technique and performance.

International Journal of Sports Physiology and Performance.

This manuscript is presented on the following pages as resubmitted clean version that was accepted for publication.

The effect of Differential Training on female volleyball spike jump technique and performance

Original investigation

Philip X. Fuchs[1,2], Andrea Fusco[1,2], Jeffrey W. Bell[3], Serge P. von Duvillard[1], Cristina Cortis[2], Herbert Wagner[1]

[1] University of Salzburg, Salzburg, Austria

[2] University of Cassino and Southern Lazio, Cassino, Italy

[3] Southwest Minnesota State University, Marshall, Minnesota, USA

Corresponding author:

Philip X. Fuchs

Department of Sports Science and Kinesiology

University of Salzburg

Schlossallee 49

A-5400 Hallein-Rif

Phone: +43 662 8044-4879

Email: philip.fuchs@sbg.ac.at

Running head: Differential Training for spike jumping

Abstract word count: 248

Text-only word count: 3390

Number of figures and tables: 4

Conflict of Interest: None

Abstract

Purpose: The purpose of this investigation was to determine the effect of in-season Differential Training on volleyball spike jump technique and performance in elite-level females.

Methods: During the season, spike jumps of 12 elite female players (Austrian Volleyball League Women) were recorded by 13 Qualisys Oqus cameras (250 Hz) and an AMTI force plate (2000 Hz). A first measurement was conducted at the beginning of the investigation. Two identical measurements were repeated after a first and a second interval. The first interval served as control phase. The second was comparable in length and regular program but included Differential Training (6 weeks, 8 sessions of 15-20 min) as a modified warm-up. It addressed specific performance determinants. Analyses of variances were calculated for the three measurements and for the development during control and intervention phase.

Results: Initial jump height (0.44±0.09 m) changed by -4.5% during control phase and +11.9% during intervention (P<.001, $p\eta^2$=.70). All approach variables, arm backswing, and velocity conversion strategy improved compared to control phase (Δ%: 6.1-51.2%, P<.05, $p\eta^2$: .40-.80). Joint angles, countermovement depth, maximal angular velocities and torso incline were not affected (Δ%: -2.9-9.1%, P: .066-.969, $p\eta^2$: .00-.27).

Conclusions: In-season Differential Training led to technical adaptations and increased spike jump height in elite females. The Differential Training program allowed players to experience a range of adaptability and to adjust toward an individual optimum in technical components of performance determinants. Coaches are encouraged to apply technical Differential Training to elite athletes and to target specifically biomechanical performance factors.

Keywords: Kinematics, in-season intervention, individual optimization, coordination, movement variability

Introduction

Volleyball is played competitively by both sexes; however, the number of active participants is higher in females compared to males. For example, 88% of all volleyball competitors in US high schools are reported to be females[1].

A fundamental performance criterion in volleyball is jump height. It correlates well with overall competition level[2] and is a main target in volleyball training[3]. This is especially important for the spike jump as increased jump height allows more options for various actions and increases the effective court size for the strike. The spike jump is the most frequently used attack and is considered decisive for winning matches[4].

The spike jump is a technically complex movement, characterized by a horizontal approach, asymmetric leg placement, conversion of horizontal-to-vertical velocity, counter movement, and arm swing[5,6]. However, the role of these characteristics must be addressed carefully depending on the target group because of sex-specific differences[7]. Differences between sexes occur in approach speed and orientation step length, strategy to transfer approach velocity via plant angle and horizontal ground reaction forces on the side of the striking arm, vertical center of mass (CoM) displacement, minimal knee and hip angles, maximal torso incline, maximal backswing of the arms and angular shoulder velocities[7]. Moreover, all these characteristics affect jump performance. In fact, a multitude of these variables correlate with jump height, specifically in female players[8,9].

A technique optimizing training approach may be a favorable option when executing complex movements such as the spike jump, especially in female athletes due to technical deficits[7] in performance determinants[8]. Traditional approaches are described[10] to provide models of movements that the athletes attempt to replicate. Based on external feedback, input, and corrections by the coach, the athlete repeats movements. With each repetition, the athlete attempts to reduce the differences in movement characteristics between the performed movement and the proposed or ideal model. Thus, an athlete attempts to emulate and achieve a predefined model. Consequently, such approaches allow to learn and to perform predefined patterns that work in stable conditions. However, predefined models do not consider the individuality of an athlete and are less adaptive to dynamic situations. Therefore, the traditional approach has limitations when aiming for the acquisition of individual and optimal patterns in dynamic conditions. An effective method that may enhance traditional learning approach to optimize technique may be Differential Training. It was described by Schöllhorn et al.[10] and is based on the fact that a movement is never repeated identically[11]. The individuality of optimal movement patterns also increases with the technical complexity (e.g. number of involved, well coordinated joints) of the task[12]. Consequently, Differential Training seems suitable to optimize complex movements in dynamic environments such as the volleyball spike jump through individual adaptations.

Previous investigations corroborated positive effects of Differential Training in game sports specific skills and general performance (e.g. vertical jumps) after 4-10 weeks, 2 sessions per week, and 15-25 min per session[10,13]. In contrast to a traditional approach, the fundamentals of Differential Training are 1) not to instruct a predefined ideal pattern of the movement, 2) not to repeat such predefined pattern multiple times with the goal to imitate it, and instead 3) to deliver types and ranges of movement variability that are adapted accordingly to the skill level of the athletes (e.g. lower skill level requires geometric rather than rhythmic variations and larger range of variability due to the reduced ability to access certain dimensions of the movement and to distinguish subtle body sensations, respectively).

The objective of this study was to investigate the effect of a Differential Training based intervention on movement characteristics and performance in female volleyball spike jump. We hypothesized that female volleyball players would show beneficial adaptations in spike jump technique and jump height after a 6-weeks technique oriented Differential Training.

Methods

Participants

A female volleyball team (*n*=12) competing in the Europa Cup and the highest division in Austria (Austrian Volleyball League Women) participated in this study (age: 22.8±3.7 years; body height: 1.78±0.09 m; body mass: 69.9±9.4 kg; positions: 2 setters, 2 libera, 2 blockers, 5 universals, 1 diagonal). For all players, the spike-striking arm defined the dominant side. The institutional research ethics committee of the University of Salzburg approved the study in accordance with the Declaration of Helsinki. All players signed an informed consent before the data collection and declared to be free of injuries.

Study design

The study was conducted during the first half of the competitive season. The development of jump performance when regular training is implemented during this period is well documented[14]. Three identical testing sessions were conducted at the start of the season, after 6.5 weeks, and again after 12.5 weeks. Throughout the data collection, there were no differences in regular training scheme between the two intervals. Moreover, both intervals were comparable in training (first interval: 8.8±0.3 hours per week, second interval: 7.7±0.2 hours per week) and competition (1 international and 7 national matches per interval) loads. The first 6.5 weeks of measurement served as control phase. A Differential Training intervention was implemented with no changes during the subsequent 6 weeks. This design allowed assessing the effect of the intervention program by comparing the developments during intervention and control phase. The same design has been used previously[14]. Due to ethical reasons and the limited number of available elite-level female volleyball players, a control group was logistically not feasible[14].

Training intervention

Eight sessions of Differential Training with focus on technique (15-20 minutes with at least 48 hours between sessions) were integrated into the regular volleyball training as modified warm-up. Each of the first five sessions targeted one of five specific performance determinants (i.e. arm swing, upper body usage, countermovement, approach, asymmetric leg functionality). The final three sessions combined the specific characteristics into complex movements and finally into the complete spike jump movement. In accordance with the principles of Differential Training, the athletes did not repeat movements in an attempt to follow a specific pattern. Instead, they were instructed to perform multiple variations to identify the individual optimal pattern. The variations are summarized in Table 1. Three systematic and replicable sequences were applied for the implementation of the variations, namely 1) alternating sequences: The movement was first implemented in an extremely detrimental fashion (e.g. too large joint angle) and then in the other detrimental extreme (e.g. too small joint angle). After such pair of extremes, the movement was implemented two more times in less detrimental fashions. This procedure was repeated several times, approaching toward an individual optimum that was found in between both extremes); 2) sequential sequences: After performing the movement once in an extremely detrimental fashion (e.g. too large joint angle), it was executed several times, each time in less detrimental fashion (e.g. decreasing joint angle) and hereby approaching towards an individual optimum; 3) experimental sequences: The participants performed several individual attempts to recall the previously experienced individual optimum. The instructions for the participants did not explain this methodology but instead defined the movement execution for the upcoming sequence. The instructions were given before each new sequence. The number of executions per sequence was chosen by each participant individually until the individual optimum was found. During all tasks, players aimed to jump as high as possible and experience their sensations and the effect of each variation on the performance. Before the first training session, the athletes were informed of 1) the principles of Differential Training, 2) that some of the instructions will intentionally be detrimental for jump height, and 3) the success of the intervention does not depend on the jump performance during the single trials but on the strict implementation of instructions although they may create detrimental conditions and feel flawed.

**** Insert Table 1 about here ****

Data collection and processing

Each of the three measurement sessions followed the same procedure. The players performed multiple general countermovement jumps and spike jumps with increasing intensity for specific warm-up. These also served for familiarization with laboratory conditions. The athletes self-selected an optimal approach distance and angle between approach and spiking direction. Subsequently, they performed 5 spike jumps as high as possible, contacting a force plate on the ground with only the dominant leg and imitating an arm strike. In case of incorrect feet positioning, trials were repeated. Voluntary breaks between trials were allowed to prevent fatigue.

A Cleveland Clinic Marker set (Motion Analyses Corp, Santa Rosa, USA) of 51 reflective markers including lower limb clusters[15] was captured by 13 Oqus cameras (Qualisys AB, Gothenburg, Sweden) at a measure frequency of 250 Hz. In agreement with the specifications for the Cleveland Clinical Marker set, segments were defined on the basis of proximal and distal joint centers. Data were managed in Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden). Filtering[16] and all further analyses were performed via Visual3D software (C-Motion, Inc., Rockville, MD, USA). Visual3D calculates the CoM via segment positions and regression equations[17]. The sagittal change of angle between adjacent segments presents the extension in knees, hips, and shoulders (knee: shank-thigh, hip: thigh-torso, shoulder: upper arm-torso).

A force plate (120x60 cm; AMTI, Watertown, MA, USA) recorded ground reaction forces of the dominant leg at 2000 Hz. Data were filtered at 50 Hz by a fourth-order low-pass Butterworth and normalized to body weight.

Definitions and variables

The difference between the lowest CoM position and CoM position in still stance determined lowering of CoM, normalized to CoM position in still stance. Minimal joint angles (for knees and hips) and maximal angular velocities (for shoulders) were computed. Extension (for knees and hips) and flexion (for shoulders) defined positive values. All other variables are shown in Figure 1.

**** Insert Figure 1 about here ****

Statistical Analyses

PASW Statistics 18.0 (SPSS Inc., Chicago, IL, USA) and Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA) were used for statistical analyses. Normal distribution was assessed via Shapiro-Wilk test, skewness, and kurtosis. Values are mean ± standard deviation with 95% confidence intervals.

Analysis of variance (ANOVA) with repeated measures was calculated for differences between the three measurements (1 factor, 3 levels) and for the differences between percentage changes during the two phases (1 factor, 2 levels). For post hoc pair-wise comparison, Bonferroni correction was performed accounting for the number of analyses of interest.

The significance level was set a priori at $\alpha<.05$. Statistical power was presented as $1-\beta$ and effect size as partial eta square ($p\eta^2$). Effects were defined as small, medium, and large if $p\eta^2$ exceeded the thresholds of .10, .25, and .40, respectively[18].

Results

The players participated in 90% of all intervention sessions. One player missed three sessions, another player missed two, and five players missed one. All players completed all measurements. During the investigation, one injury (ankle sprain) was reported. The injury happened one week before the second measurement. The player recovered and completed the measurement.

ANOVA results for differences across the three measurements are presented in Table 2. Pair-wise comparisons revealed 2 (control phase) and 9 (intervention phase) significant differences out of 15 tests. Every single athlete increased performance during the intervention phase.

**** Insert Table 2 about here ****

ANOVA results for differences between the changes during control and intervention phase are included in Figure 2.

**** Insert Figure 2 about here ****

Discussion

Most players had no previous experience with Differential Training and reported positive feedback after the intervention. They were motivated and strictly followed the instructions, also in movement variations that felt erroneous and detrimental for performance. We consider the *a priori* information regarding the concept of the training program important. These allowed the athletes to understand and commit to the implementation of instructions that may not have been in agreement with their idea of the targeted movement. We observed no hesitation in performing detrimental variations and no distractive competition between players. This provided great value to experience a range of variations and to process the sensations individually. After the intervention, players reported during informal, verbal exchange that they felt more capable to engage beneficial movement characteristics and to compensate unavoidable and negative conditions more effectively and naturally.

The objective of the study was to reduce the known decline in jump performance during the volleyball season and to improve performance. During the control phase of regular training, jump height tended to decrease by 4.5% (P=.094). In comparison, a previous investigation reported a higher and,significant decline by 5.4% for the same seasonal period[14]. However, this may be partially explained by the difference in work load between the samples of the current and previous[14] study. Work load and insufficient recovery (3 matches per week) were described as main reasons for the reduction in performance during the season[14]. In the current study, the team competed in only 1-2 matches per week. Accounting for the physical demands, the trend observed in the current study is in agreement with previous findings[14].

During the intervention phase, jump height increased by 11.9% and large effect sizes were observed for differences over the three measurements and for the comparison of developments during both phases. Four items should be considered when assessing the magnitude and practical relevance of this change: 1) Without intervention, a loss in performance during this period is to be expected and has been reported for the control phase and in the literature[14]; 2) jump height after the intervention was 6.4% higher than in the beginning of the season when the performance is supposed to be optimal as result of the pre-season; 3) several previously conducted interventions yielded increases in jump height by 5.4-11.6% during pre-season (12-36 sessions)[19-22] and by 3.9-5.4% during the season (8-24 sessions)[14,23]; and 4) the current positive effect was achieved within 8 sessions, 15-20 min each, integrated into the regular training as modified part of the warm-up, by a program that represents low work load and does not require any compromises in regular volleyball or strength training. The current intervention program required approximately 140 min of intervention training in total, compared to 540-3840 min in previous investigations[19,21,23]. These 140 min of intervention were included in the warm-up and did not add extra training minutes. Other studies did not report the length of the sessions[14,22] or the intervention did not include additional training but an adaption of regular training (e.g. application of electromyostimulation during the regular strength training)[20]. Because of increased work load and reduced recovery times during the competitive season, in-season interventions that involve no or low additional work load and impact on regular training are preferred.

All variables reflecting the approach, asymmetric leg activity in velocity conversion, and arm backswing improved greatly in both discrepancy of percentage changes (6.1-51.2%) and large effect sizes ($p\eta^2$: .40-.80) in the phase comparison. Lowering CoM was not significant (P=.08) and no differences were found for minimal hip and knee angles, maximal torso incline, and maximal angular shoulder velocities. These results indicate positive effects of the intervention on the technical implementation of the volleyball spike jump. However, the effects are restricted to specific characteristics. The intervention clearly and remarkably resulted in positive adaptations in the backswing of arms, approach speed, and capacity to transfer horizontal velocity of the dominant leg (larger orientation step, smaller plant angle, and greater maximal horizontal ground reaction force). These contributed to the height of the volleyball spike jump[5,8]. Therefore, the increase in jump height was positively affected by the adaptations in approach speed, arm backswing, and conversion strategy. The lack of effect in countermovement, torso incline, and arm swing velocity may be the result of the relationship of these criteria with strength abilities[24]. The intervention did not target strength abilities; it predominantly focused on technique. Thus, we cannot expect strength abilities to be affected by the intervention. The adaptation of muscular capacity utilizing these criteria may have been limited.

Muscular training for the lower limbs is common practice to improve jump height[3] and volleyball clubs at elite-level generally utilize specific conditioning programs. A strength of the current technical training program is that it does not add to physiological load and can be implemented in addition to regular volleyball and conditioning training. This intervention did not require additional training time but was implemented as modified part of the warm-up within the volleyball training.

Another reason for the success of this program may be the specificity of variations. Previous Differential Training programs included variations in a comparably wide range of characteristics that were not closely related to performance determinants (e.g. turning the head during kicking a ball)[10,13,25]. In the current program, the targeted characteristics were strictly derived from performance determinants on the basis of previous findings[5,8,9,26]. Schöllhorn, Hurth, Kortmann, and Müller[27] attempted to identify biomechanical variables that explain the performance with the goal to address them in Differential Training. This suggests that the focus on performance determinants is in agreement with the concept of Differential Training and may increase its effectiveness. It is important to understand that the current program did not predefine the optimal pattern but allowed the athletes to experience variability specifically in relevant movement characteristics. While focusing on these characteristics, the program facilitated self-regulation[11] and individual optimization[10].

This type of approach and methodology leads to a challenge for coaches. Coaches that apply these types of Differential Training require a certain biomechanical understanding of the target movement and precise knowledge of the most relevant characteristics to be directed. Variations that target a wide range of characteristics can be presumed to also have positive effects as it has been reported in other sports[10,13,25]. However, we cannot assess whether the magnitude of effects by such programs would be comparable with the current results. Another challenge is to adapt the range of variability[28] and training time spent on single characteristics accordingly to the athletes' skill and progress during the training sessions. In this intervention, the range of variability was broadened when athletes showed difficulties to distinguish the differences. More variations related to a specific movement characteristic were added when athletes showed continuous progress at the scheduled end of a block of variations. The focus of variations was shifted to another movement characteristic when the athletes approached stagnation and lacked progress in the current characteristic. This was detected when the athletes started to be unable to execute the differences of variation characteristics and instead repeated the same pattern.

Practical Applications

Eight sessions of short Differential Training[10] positively affected volleyball spike jump technique and performance in elite-level female players during the competitive season. It appeared reasonable to define movement variations especially for biomechanical characteristics that determine the performance of the movement (e.g. approach, asymmetric leg functionality, and arm swing in the spike jump). Introducing the basic idea of Differential Training to the athletes may support the motivation to implement movement variations that may feel flawed. It is suggested that experiencing a range of movement variability facilitates self-regulation processes that initiate adjustments towards an individual optimum[10]. The current study investigated volleyball spike jump performance of elite-level female players. However, previously reported effects of Differential Training in males, various sports, age, and skill levels[10,13,25,29] indicate the transferability of the findings.

A limitation of this study may be the control phase instead of a control group. This was unavoidable due to ethical and logistical reasons and the limited accessibility to elite-level female players. First, the control and intervention phases took place during a period of the competitive season with no major changes in work loads and with no interruptions. There were also no systematic differences in the regular training between both phases. Second, the current study very closely adopted the design and schedule of a previous investigation that overcame the same challenge[14]. Previous investigation[14] reported the development of spike jump performance without intervention for the identical period of the season as in the current study. Accounting for the number of weekly matches, the agreement of both studies in the development of jump performance without intervention suggests the control phase during this period to be a reasonably reliable reference.

Conclusions

This study applied an in-season Differential Training intervention that led to technical adaptations and increased performance in the volleyball spike jump of elite-level female players. The players experienced increased movement variability during the intervention that allowed adjustments towards an individual optimum. Jump height improved by 11.9%. Differences in approach velocity, arm swing, and asymmetric leg functionality in velocity conversion showed that technique-related movement characteristics can be enhanced at high levels within a short intervention period. Adaptations in the countermovement and minimal joint angles may not be improved if muscular abilities cannot generate the required power. We conclude that the current program was a practical and effective measure to improve volleyball spike jump technique and performance in females during the competitive season.

Acknowledgments

We want to thank the players and coaches (PSV Salzburg, Austria) for participation, J. Birklbauer (University of Salzburg, Austria) for scientific consultation in Differential Training, the volleyball coaches M. Dassi and F. Guidotti (Virtus Roma Pallavolo, Italy) for practical contributions to the intervention and the assessment of developments during the control and intervention phase, and A. Martinez, C. Snyder, and G. Strutzenberger (University of Salzburg, Austria) for assistance in data collection and handling.

References

1. The National Federation of State High School Associations. *2017-18 High School Athletics Participation Survey*. http://www.nfhs.org/ParticipationStatistics/PDF/2017-18%20High%20School%20Athletics%20Participation%20Survey.pdf. Published 2018. Accessed June 20, 2019.
2. Ziv G, Lidor R. Vertical jump in female and male volleyball players: a review of observational and experimental studies. *Scand J Med Sci Spor*. 2010;20(4): 556-567.
3. Powers ME. Vertical Jump Training for Volleyball. *Strength Cond J*. 1996;18(1):18-23.
4. Palao J, Santos J, Ureña A. Effect of team level on skill performance in volleyball. *Int J Perf Anal Spor*. 2004;4(2):50-60.
5. Wagner H, Tilp M, von Duvillard SP, Müller E. Kinematic analysis of volleyball spike jump. *Int J Sports Med*. 2009;30(10):760-765.
6. Waite P. *Aggressive volleyball*. Champaign, IL: Human Kinetics; 2009.
7. Fuchs PX, Menzel H-JK, Guidotti F, Bell JW, von Duvillard SP, Wagner H. Spike jump biomechanics in male versus female elite volleyball players. *J Sport Sci*. 2019;37(21):2411-2419.
8. Fuchs PX, Fusco A, Bell JW, von Duvillard SP, Cortis C, Wagner H. Movement characteristics of volleyball spike jump performance in females. *J Sci Med Sport*. 2019;22(7):833-837.

9. Ikeda Y, Sasaki Y, Hamano R. Factors influencing spike jump height in female college volleyball players. *J Strength Cond Res*. 2017;32(1):267-273.
10. Schöllhorn WI, Hegen P, Davids K. The Nonlinear Nature of Learning - A Differential Learning Approach. *Open Sports Sci J*. 2012;5(Suppl 1):100-112.
11. Bernstein NA. *The Coordination and Regulation of Movements*. Oxford, UK: Pergamon Press; 1967.
12. Schöllhorn WI, Nigg BM, Steanyshyn DJ, Liu W. Identification of individual walking patterns using time discrete and time continuous data sets. *Gait Posture*. 2002;15(2):180-186.
13. Coutinho D, Santos S, Gonçalves B, Travassos B, Wong DP, Schöllhorn WI, Sampaio J. The effects of an enrichment training program for youth football attackers. *PloS one*. 2018;13(6): doi: 10.1371/journal.pone.0199008.
14. Newton RU, Rogers RA, Volek JS, Häkkinen K, Kraemer WJ. Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *J Strength Cond Res*. 2006;20(4):955-961.
15. Selbie WS, Hamill J, Kepple TM. Three-dimensional kinetics. In: Robertson DGE, Caldwell GE, Hamill J, Kamen G, Whittlesey SN, ed. *Research Methods in Biomechanics*. 2nd ed. Champaign, IL: Human Kinetics; 2014:151-176.
16. Woltring HJ. A Fortran package for generalized, cross-validatory spline smoothing and differentiation. *Adv Eng Softw*. 1986;8(2):104-113.
17. Dempster WT. *Space requirements of the seated operator*. Dayton, OH: Wright-Patterson Air Force Base; 1955.
18. Cohen J. A Power Primer. *Psychol Bull*. 1992;112(1):55-159.
19. Maffiuletti NA, Dubnani S, Folz M, Di Pierno E, Mauro F. Effect of combined electrostimulation and plyometric training on vertical jump height. *Med Sci Sport Exer*. 2002;34(10):1638-1644.
20. Malatesta D, Cattaneo F, Dugnani S, Maffiuletti NA. Effects of electromyostimulation training and volleyball practice on jumping ability. *J Strength Cond Res*. 2003;17(3):573-579.
21. Martel GF, Harmer ML, Logan JM, Parker CB. Aquatic plyometric training increases vertical jump in female volleyball players. *Med Sci Sport Exer*. 2005;37(10):1814-1819.
22. Newton RU, Kraemer WJ, Haekkinen K. Effects of ballistic training on preseason preparation of elite volleyball players. *Med Sci Sport Exer*. 1999;31(2):323-330.
23. Marques MC, van den Tillaar R, Vescovi JD, González-Badillo JS. Changes in strength and power performance in elite senior female professional volleyball players during the in-season: a case study. *J Strength Cond Res*. 2008;22(4):1147-1155.
24. Sheppard JM, Cronin JB, Gabbett TJ, McGuigan MR, Etxebarria N, Newton RU. Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *J Strength Cond Res*. 2008;22(3):758-765.
25. Savelsbergh GJP, Kamper WJ, Rabius J, de Koning JJ, Schöllhorn WI. A new method to learn to start in speed skating: A differencial learning approach. *Int J Sport Psychol*. 2010;41(4):415-427.

26. Lees A, Vanrenterghem J, De Clercq D. Understanding how an arm swing enhances performance in the vertical jump. *J Biomech.* 2004;37(12):1929-1940.
27. Schöllhorn WI, Hurth P, Kortmann T, Müller E. Biomechanical basis for differential learning in alpine skiing. In: Müller E, Lindinger S, Stöggl T, ed. *Science and Skiing IV*. Graz, Austria: Meyer & Meyer Sport; 2009:454-464.
28. Beckmann H, Winkel C, Schöllhorn WI. Optimal range of variation in hockey technique training. *Int J Sport Psychol*. 2010;41(Suppl):5-10.
29. Wagner H, Müller E. The effects of differential and variable training on the quality parameters of a handball throw. *Sport Biomech.* 2008;7(1):54-71.

Figure captions

Figure 1. Volleyball spike jump from approach to take-off, including variables and definitions.

Note: CoM=center of mass; v=velocity; CoM_Z=vertical displacement of center of mass; g=gravitational constant.

Figure 2. Change of all investigated variables during control and intervention phase expressed in percentage, including statistical results for differences between phases.

Note: A positive change in plant angle is defined as beneficial for velocity conversion (i.e. decreased plant angle); Max.=maximal; Min.=minimal; D=dominant; ND=non-dominant; CoM=center of mass; velocity°=angular velocity; *=(*P*=.020); **=(*P*=.002); ***=(*P*<.001).

Figures

Figure 1

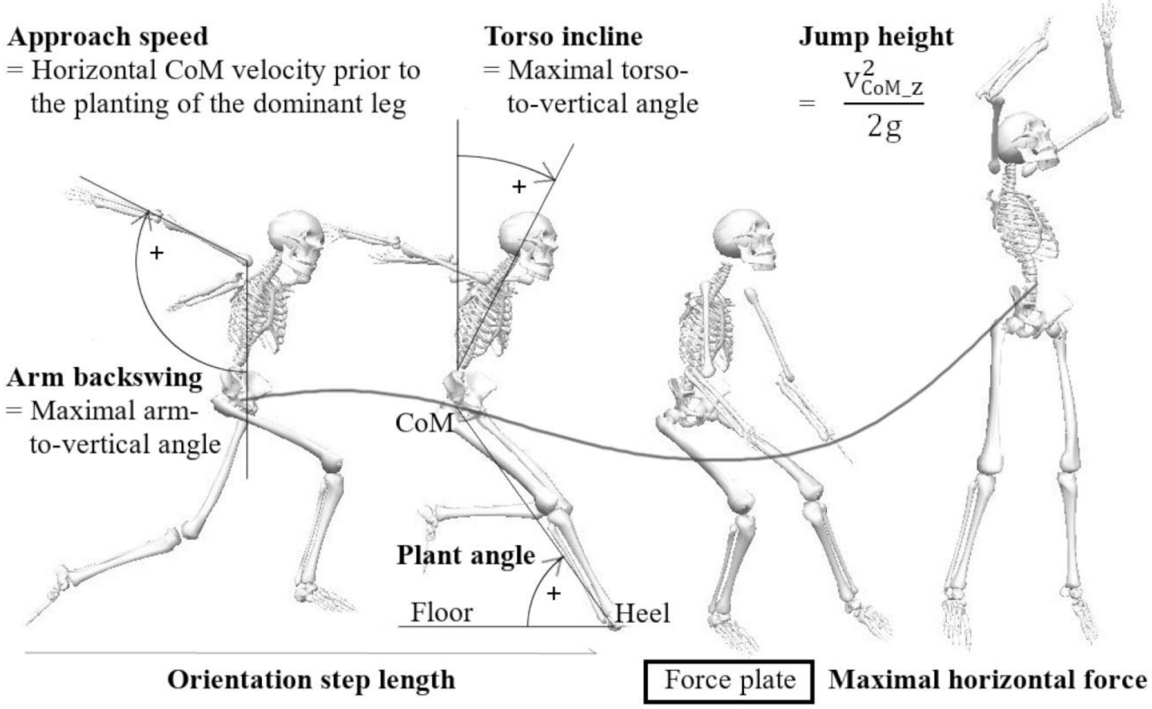
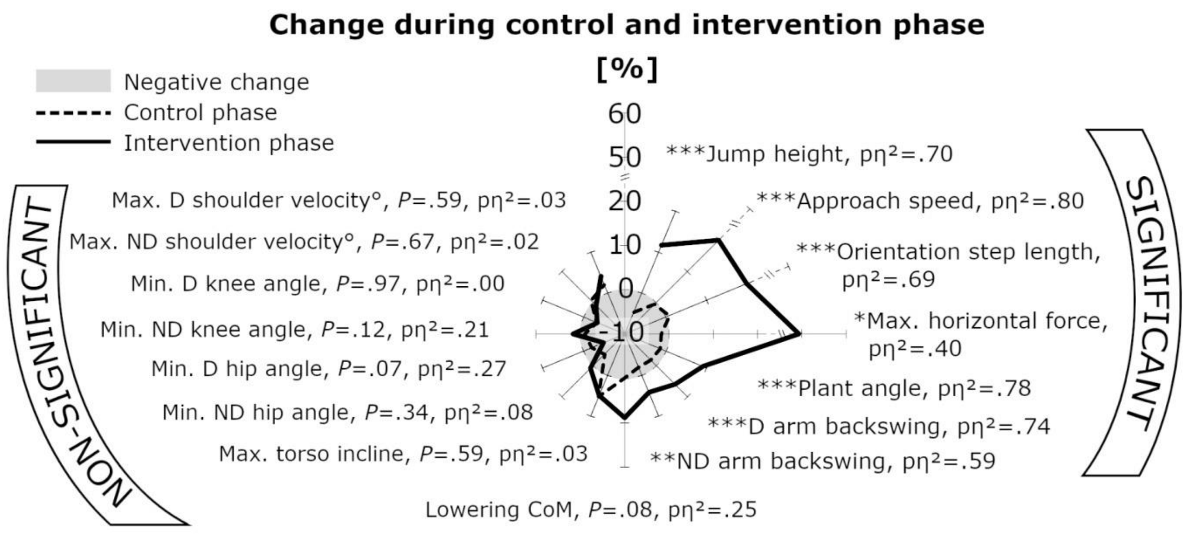


Figure 2



Tables

Table 1. Movement characteristics and classification of variations applied in the current Differential Training program. CoM=Center of mass.

Arm swing *	**Upper body usage ***	**Countermovement #**	**Approach ‡**	**Asymmetric leg functionality #**
Maximal arm-to-vertical angle during backswing •Large •Small Final position of the arms •45° in front of torso •90° in front of torso •135° in front of torso Velocity • Fast • Slow De-acceleration in the end • Late and great • Early and low	Initial position of the torso •Low •High Final position of the torso •Forward lean •Straight •Backwards lean Velocity •Fast •Slow De-acceleration in the end •Late and great •Early and low	Depth •Low •High Speed •Fast •Slow Initial height of CoM •Low •High Transition from counter-movement to push-off •Pause •Smooth •Rushed	Speed •Fast •Slow Step length •Short •Large Vertical CoM movement •Downwards •Horizontal •Upwards-downwards (=hopping)	Weight distribution... ...during countermovement •Rear leg •Front leg ...during upwards acceleration •Rear leg •Front leg Stopping horizontal velocity •Rear leg •Front leg

Note: During the first five sessions addressing one of the five determinants specifically, variations were performed as follows: *=no approach and no jump, then no approach but jump, then approach and jump; #=no approach but jump, then approach and jump; ‡=approach but no jump, then approach and jump. During the final three sessions, the single determinants were combined and always performed with approach and jump.

Table 1. Means ± standard deviations (SD), 95% Confidence Intervals (CI), and results of ANOVA with repeated measures.

Variable	Mean ± SD 95% CI Lower Bound – 95% CI Upper Bound Control phase: Start	Control phase: End / Intervention phase: Start		Intervention phase: End	*P*	pη²	1-β
Jump height [m]	0.44 ± 0.09 0.38 – 0.50	0.42 ± 0.08 0.36 – 0.47	*	0.47 ± 0.08 0.42 – 0.52	<.001	.57	1
Approach speed [m·s^{-1}]	2.49 ± 0.24 2.34 – 2.65	2.48 ± 0.19 2.36 – 2.59	*	2.98 ± 0.21 2.85 – 3.12	<.001	.82	1
Orientation step length [m]	1.06 ± 0.14 0.97 – 1.15	1.05 ± 0.12 0.97 – 1.13	*	1.26 ± 0.11 1.19 – 1.33	<.001	.69	1
Plant angle [°]	75 ± 5 71 – 78	76 ± 5 72 – 79	*	69 ± 3 67 – 71	<.001	.72	1
Max. horizontal force [N·kg^{-1}]	5.54 ± 2.88 3.70 – 7.37	5.45 ± 1.31 4.61 – 6.28	*	8.15 ± 2.09 6.82 – 9.48	<.001	.60	1
Lowering CoM [%]	22 ± 4 20 – 25	22 ± 5 19 – 25	(*)	24 ± 5 21 – 28	.017	.31	.75
Min. ND knee angle [°]	112 ± 5 109 – 115	111 ± 6 107 – 114		113 ± 6 109 – 116	.259	.12	.27
Min. D knee angle [°]	96 ± 7 91 – 100	93 ± 6 89 – 97		90 ± 6 87 – 94	.003	.41	.92
Min. ND hip angle [°]	113 ± 8 108 – 118	109 ± 9 103 – 115		110 ± 8 105 – 115	.262	.12	.27

Min. D hip angle [°]	105 ± 8 99 – 110		103 ± 8 98 – 109	*	98 ± 7 94 – 103	<.001	.50	.98
Max. torso incline [°]	37 ± 7 32 – 42	#	39 ± 8 34 – 44		41 ± 8 36 – 46	.007	.37	.85
ND arm backswing [°]	116 ± 9 111 – 122		114 ± 9 108 – 119	*	119 ± 7 114 – 124	.014	.32	.77
D arm backswing [°]	118 ± 10 111 – 124	#	116 ± 10 110 – 122	*	123 ± 7 118 – 127	.001	.59	.98
Max. angular ND shoulder flexion velocity [°·s^{-1}]	905 ± 94 846 – 965		913 ± 73 867 – 959		905 ± 64 864 – 946	.933	.01	.01
Max. angular D shoulder flexion velocity [°·s^{-1}]	880 ± 113 808 – 952		898 ± 96 837 – 959		936 ± 106 869 – 1003	.020	.30	.73

Note: Start=Start of the investigation period; Mid=End of control phase and beginning of intervention; End=End of the intervention; D=Dominant; ND=Non-dominant; Min.=Minimal; Max.=Maximal; #=Significant (P<.05) difference between start and mid of the period; *=Significant (P<.05) difference between mid and end of the period; * and # are in brackets if the difference is not significant (P<.05) after Bonferroni correction.

7 Summary and perspectives

The objective of this doctoral thesis was to investigate sex differences in movement characteristics of volleyball spike jumps, to identify female performance determinants, and to assess the efficacy of a technical-oriented training intervention specifically for females.

Spike jump biomechanics in male versus female elite volleyball players

Holistic approaches of data collection and assessment are important to improve the knowledge of technical complex movements. Thanks to kinematic, kinetic, and neuromuscular data, this study provided valuable insights in the volleyball spike jump. Sex differences in jump height, movement characteristics (e.g. approach speed, arm swing, countermovement) and muscular coordination were revealed. Moreover, the correlation between secondary variables that define the technical implementation of the movement was assessed. This contributed to the understanding of the role of specific technical characteristics (e.g. the importance of plant angle for approach speed and velocity conversion). Such information can be valuable for training strategies that aim for adaptations in technique.

Movement characteristics of volleyball spike jump performance in females

Previous research on performance determinants in the volleyball spike jump were mainly implemented in male players and sex differences were revealed in the first investigation of this thesis. The second study analyzed the relationship between movement characteristics and spike jump performance (i.e. jump height and ball velocity) in female players. For jump height, correlation and regression results underlined the importance of a dynamic approach, velocity conversion and arm swing to upwards acceleration during push-off and to increase angular maximal velocities of the lower limbs. Therefore, these criteria represented key factors for practical training in female players. For spike velocity, maximal angular velocities in the upper body tended to be influential. However, the individually preferred striking technique (i.e. elevation style versus backswing style) should be taken into account, especially when assessing the importance of maximal angular velocity in internal shoulder rotation.

The effect of Differential Training on female volleyball spike jump technique and performance

The third study showed remarkable positive effects on performance and technique in elite female players after a 6-week differential training during the competitive season. This was shown by increased jump height (+16.6% compared with control phase) and adaptations in several movement characteristics (e.g. approach speed, arm swing, velocity conversion strategy). All of the technical characteristics were previously found to determine female spike jump performance. The differential training program focused specifically on technical-coordinative performance determinants and added minimal physiological loads to the athletes' regular training schedule. Therefore, such type of differential training can be suggested to enhance spike jump performance in high level female players.

Overall, the combined outcomes of these dissertation studies corroborated that identical movement patterns between females and males cannot be presumed. Sex-specific characteristics in technical complex movements should be considered in scientific research and practical training. Consequently, performance determinants must be investigated specifically for sexes. Then, sex-specific training measures can be developed that focus on specific performance determinants. Such training programs are effective and can improve high level performance remarkably.

More detailed recommendations can be found in the articles' conclusions section.

8 Tables

3 Sex differences in performance and technique

Table 1. Examples for differences in characteristics during basic movements between sexes. ii

5 Research deficit

Table 2. Studies that investigated sex differences or effects on female volleyball spike jump performance iii

ARTICLE 1

Table I. MANOVA and ANOVA results for females and males. Values are mean ± SD ... iv

Table II. Correlation of secondary variables. The selection includes variables related to biomechanical key aspects for the performance: approach, velocity transfer, upper body lean and arm swing vi

ARTICLE 2

Table 1. Significant correlation results, displaying mean ± standard deviation (SD), 95% confidence interval (CI), significance level (p), and correlation coefficient (r) ....**Fehler! Textmarke nicht definiert.**

Supplementary Table. Mean ± standard deviation, correlation coefficient (rh, rv) and significance level (ph, pv) for correlation with jump height and ball velocity, respectively, of all measured characteristics viii

ARTICLE 3

Table 1. Movement characteristics and classification of variations applied in the current Differential Training program. CoM=center of mass ix

Table 2. Means ± SD, 95% Confidence Intervals (CI), and results of ANOVA with repeated measures 1

9 Figures

2 Mechanisms of the volleyball spike jump

Figure 1. Volleyball spike jump from approach to strike. The visualization depicts a computed 3D-model on the basis of actual kinematic data of a male right-handed player and the calculation of CoM during approach until take-off to derive approach speed and jump height via CoM velocity ii

3 Sex differences in performance and technique

Figure 2. Biological sex differences in A) the distribution of muscle cross-sectional area, B) glenoid size and shape, C) muscle mass in upper and lower body, and D) muscle architecture in the lower limbs iii

ARTICLE 1

Figure 1. Overall time-frame and definition of phases, terms, and angles relative to the vertical axis iv

Figure 2. Mean female and male values for maximal muscle activation of lower extremity muscles of the dominant and non-dominant side vi

Figure 3. Multivariate regression analyses between jump height and approach velocity, vertical CoM decrease, torso incline, and plant angle, including sex as control variable **Fehler! Textmarke nicht definiert.**

Figure 4. Multivariate regression analyses between jump height and maximal angular velocity of dominant and non-dominant knees and shoulders, including sex as control variable viii

ARTICLE 2

Fig. 1. Time window of analyses, phases, and variables of the volleyball spike jump ix

ARTICLE 3

Figure 1. Volleyball spike jump from approach to take-off, including variables and definitions 1

Figure 2. Change of all investigated variables during control and intervention phase expressed in percentage, including statistical results for differences between phases 2

10 References

Abe, T., Brechue, W. F., Fujita, S., & Brown, J. B. (1998). Gender differences in FFM accumulation and architectural characteristics of muscle. *Medicine and Science in Sports and Exercise, 30*(7), 1066-1070.

Abe, T., Kearns, C. F., & Fukunaga, T. (2003). Sex differences in whole body skeletal muscle mass measured by magnetic resonance imaging and its distribution in young Japanese adults. *British Journal of Sports Medicine, 37*(5), 436-440.

Abián, J., Alegre, L. M., Lara, A. J., Rubio, J. A., & Aguado, X. (2008). Landing differences between men and women in a maximal vertical jump aptitude test. *Journal of Sports Medicine and Physical Fitness*, *48*(3), 305-310.

Adams, J. A. (1976). Issues for a Closed-Loop Theory of Motor Learning. In G. E. Stelmach (Ed.), *Motor Control* (pp. 87-107). New York, NY: Academic Press.

Alegre, L., Lara, A., Elvira, J., & Aguado, X. (2009). Muscle morphology and jump performance: gender and intermuscular variability. *Journal of Sports Medicine and Physical Fitness, 49*(3), 320-326.

Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics, 6*(2), 224-243.

Baumann, H., & Reim, H. (1994). *Bewegungslehre*. Frankfurt am Main: Diesterweg.

Bernstein, N. A. (1967). The coordination and regulation of movements. Oxford: Pergamon.

Bobbert, M. F., & van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal of Biomechanics, 21*(3), 249-262.

Bojsen-Møller, J., Magnusson, S. P., Rasmussen, L. R., Kjaer, M., & Aagaard, P. (2005). Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *Journal of Applied Physiology, 99*(3), 986-994.

Chen, P., Huang, C., & Shih, S. (2011). *Differences in 3D kinematics between genders during volleyball spike.* Paper presented at the Proceedings of the Congress of the International Society of Biomechanics. Brussels.

Chiu, M.-C., & Wang, M.-J. (2007). The effect of gait speed and gender on perceived exertion, muscle activity, joint motion of lower extremity, ground reaction force and heart rate during normal walking. *Gait & Posture*, *25*(3), 385-392.

Chu, Y., Fleisig, G. S., Simpson, K. J., & Andrews, J. R. (2009). Biomechanical comparison between elite female and male baseball pitchers. *Journal of Applied Biomechanics, 25*(1), 22-31.

Chumanov, E. S., Wall-Scheffler, C., & Heiderscheit, B. C. (2008). Gender differences in walking and running on level and inclined surfaces. *Clinical Biomechanics, 23*(10), 1260-1268.

Davids, K., Glazier, P., Araujo, D., & Bartlett, R. (2003). Movement systems as dynamical systems. *Sports Medicine*, *33*(4), 245-260.

Dhawale, A. K., Smith, M. A., & Ölveczky, B. P. (2017). The role of variability in motor learning. *Annual Review of Neuroscience, 40*, 479-498.

Fatouros, I. G., Jamurtas, A. Z., Leontsini, D., Taxildaris, K., Aggelousis, N., Kostopoulos, N., & Buckenmeyer, P. (2000). Evaluation of plyometric exercise training, weight training, and their combination on vertical jumping performance and leg strength. *The Journal of Strength and Conditioning Research, 14*(4), 470-476.

Ferber, R., Davis, I. M., & Williams III, D. S. (2003). Gender differences in lower extremity mechanics during running. *Clinical Biomechanics, 18*(4), 350-357.

Fitts, P. M., & Posner, M. I. (1967). *Learning and Skilled Performance in Human Performance*. Belmont, CA: Brooks-Cole.

FIVB. (2019). FIVB History. Retrieved from http://www.fivb.org/EN/FIVB/FIVB_History.asp

Forthomme, B., Croisier, J.-L., Ciccarone, G., Crielaard, J.-M., & Cloes, M. (2005). Factors Correlated With Volleyball Spike Velocity. *The American Journal of Sports Medicine, 33*(10), 1513-1519.

Hamill, J., von Emmerik, R. E. A., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14*, 297-308.

Häkkinen, K., & Pakarinen, A. (1993). Muscle strength and serum testosterone, cortisol and SHBG concentrations in middle-aged and elderly men and women. *Acta Physiologica Scandinavica, 148*(2), 199-207.

Hsieh, C., & Christiansen, C. L. (2010). The effect of approach on spike jump height for female volleyball players. *International Journal of Sports Science & Coaching, 5*(3), 373-380.

Hsieh, C., & Heise, G. D. (2008). *Arm swing of volleyball spike jump performance between advanced and recreational female players.* Paper presented at the Fourth North American Congress on Biomechanics. Ann Arbor, MI.

Ikeda, Y., Sasaki, Y., Sorimachi, S., & Hamano, R. (2017). Factors influencing spike jump height in female college volleyball players. *The Journal of Strength and Conditioning Research, 32*(1), 267-273.

Janssen, I., Heymsfield, S. B., Wang, Z., & Ross, R. (2000). Skeletal muscle mass and distribution in 468 men and women aged 18–88 yr. *Journal of Applied Physiology, 89*(1), 81-88.

Kerrigan, D. C., Todd, M. K., & Croce, U. D. (1998). GENDER DIFFERENCES IN JOINT BIOMECHANICS DURING WALKING Normative Study in Young Adults. *American Journal of Physical Medicine & Rehabilitation, 77*(1), 2-7.

Laffaye, G., Wagner, P. P., & Tombleson, T. I. (2014). Countermovement jump height: Gender and sport-specific differences in the force-time variables. *The Journal of Strength and Conditioning Research, 28*(4), 1096-1105.

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics, 37*(12), 1929-1940.

Liu, H., Leigh, S., & Yu, B. (2009). *Upper extremity motion sequence in javelin throwing.* Paper presented at the 33rd Conference of the American Society of Biomechanics. State College, PA.

Maffiuletti, N. A., Dugnani, S., Folz, M., Di, E. P., & Mauro, F. (2002). Effect of combined electrostimulation and plyometric training on vertical jump height. *Medicine & Science in Sports & Exercise, 34*(10), 1638-1644.

Malatesta, D., Cattaneo, F., Dugnani, S., & Maffiuletti, N. A. (2003). Effects of electromyostimulation training and volleyball practice on jumping ability. *The Journal of Strength and Conditioning Research, 17*(3), 573-579.

Markovic, G. (2007). Does plyometric training improve vertical jump height? A meta-analytical review. *British Journal of Sports Medicine, 41*(6), 349-355.

Martel, G. F., Harmer, M. L., Logan, J. M., & Parker, C. B. (2005). Aquatic plyometric training increases vertical jump in female volleyball players. *Medicine & Science in Sports & Exercise, 37*(10), 1814-1819.

McMahon, J. J., Rej, S. J. E., & Comfort, P. (2017). Sex differences in countermovement jump phase characteristics. *Sports, 5*(1), 8-18.

Merrill, A., Guzman, K., & Miller, S. L. (2009). Gender differences in glenoid anatomy: an anatomic study. *Surgical and Radiologic Anatomy, 31*(3), 183-189.

Nelson, J. K., Thomas, J. R., Nelson, K. R., & Abraham, P. C. (1986). Gender Differences in Children's Throwing Performance: Biology and Environment. *Research Quarterly for Exercise and Sport*, *57*(4), 280-287.

Newell, K. M. (1985). Coordination, control and skill. In D. Goodman, R. B. Wilberg, & I. M. Franks (Eds.), *Differing Perspectives in Motor Learning, Memory, and Control* (pp. 295-317). North-Holland: Elsevier Science Publishers.

Newton, R. U., Kraemer, W. J., & Haekkinen, K. (1999). Effects of ballistic training on preseason preparation of elite volleyball players. *Medicine & Science in Sports & Exercise, 31*(2), 323-330.

Newton, R. U., Rogers, R. A., Volek, J. S., Häkkinen, K., & Kraemer, W. J. (2006). Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *The Journal of Strength and Conditioning Research, 20*(4), 955-961.

Nguyen, A.-D., & Shultz, S. J. (2007). Sex differences in clinical measures of lower extremity alignment. *Journal of Orthopaedic & Sports Physical Therapy, 37*(7), 389-398.

Palao, J., Santos, J., & Ureña, A. (2004). Effect of team level on skill performance in volleyball. *International Journal of Performance Analysis in Sport, 4*(2), 50-60.

Powers, M. E. (1996). Vertical Jump Training for Volleyball. *Strength and Conditioning Journal, 18*(1), 18-23.

Römer, J., Schöllhorn, W. I., Jaitner, T., & Preiss, R. (2009). Differenzielles Lernen im Volleyball. *Sportunterricht, 58*(2), 41-45.

Sattler, T., Hadžic, V., Derviševic, E., & Markovic, G. (2015). Vertical jump performance of professional male and female volleyball players: effects of playing position and competition level. *The Journal of Strength and Conditioning Research, 29*(6), 1486-1493.

Savelsbergh, G. J., Kamper, W. J., Rabius, J., De Koning, J. J., & Schöllhorn, W. (2010). A new method to learn to start in speed skating: A differencial learning approach. *International Journal of Sport Psychology, 41*(4), 415-427.

Schöllhorn, W. I., Hegen, P., & Davids, K. (2012). The Nonlinear Nature of Learning - A Differential Learning Approach. *The Open Sports Sciences Journal, 5*(Suppl 1), 100-112.

The National Federation of State High School Associations. (2018). *2017-18 High School Athletics Participation Survey*. Retrieved from www.nfhs.org/ParticipationStatistics/PDF/2017-18%20High%20School%20Athletics%20Participation%20Survey.pdf

Thomas, J. R., & French, K. E. (1985). Gender differences across age in motor performance: A meta-analysis. *Psychological Bulletin, 98*(2), 260-282.

Tilp, M. (2003). Biomechanische Aspekte des Volleyballspiels–Sprung, Schlag und Ballflugbahn. *Volleyball–Europaweit*, 99-113.

van Emmerik, R. E. A., & van Wegen, E. E. (2000). On variability and stability in human movement. *Journal of Applied Biomechanics, 16*, 394-406.

Viera, B. L., & Ferguson, B. J. (1989). *Teaching Volleyball. Steps to Success*. Champaign, IL: Leisure Press.

Wagner, H., Pfusterschmied, J., Tilp, M., Landlinger, J., von Duvillard, S., & Müller, E. (2014). Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scandinavian Journal of Medicine & Science in Sports, 24*(2), 345-354.

Wagner, H., Tilp, M., von Duvillard, S., & Müller, E. (2009). Kinematic analysis of volleyball spike jump. *International Journal of Sports Medicine, 30*(10), 760-765.

Waite, P. (2009). *Aggressive Volleyball*. Champaign, IL: Human Kinetics.

Wilson, C., Simpson, S. E., van Emmerik, R. E. A., & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics, 7*(1), 2-9.

Yu, B., McClure, S. B., Onate, J. A., Guskiewicz, K. M., Kirkendall, D. T., & Garrett, W. E. (2005). Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *The American Journal of Sports Medicine, 33*(9), 1356-1364.

Ziv, G., & Lidor, R. (2010). Vertical jump in female and male volleyball players: a review of observational and experimental studies. *Scandinavian Journal of Medicine & Science in Sports, 20*(4), 556-567.