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SPORTS PERFORMANCE

Spike jump biomechanics in male versus female elite volleyball players

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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.

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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, Derviševic, & 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,

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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,

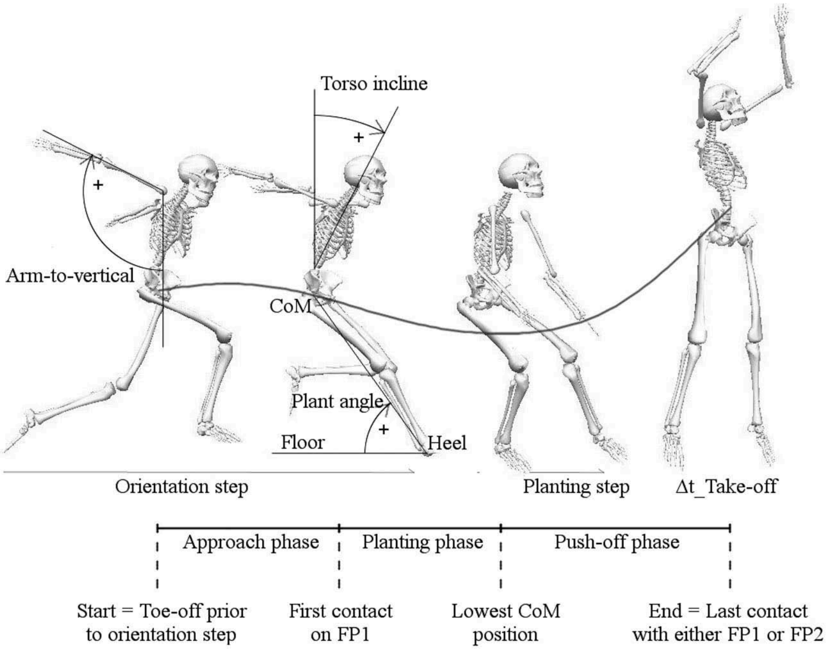

Figure 1. Overall time-frame and definition of phases, terms, and angles relative to the vertical axis.

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 ($|.46| \le r \le |.76|$, $P< .05$) 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	$p\eta^2$
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.

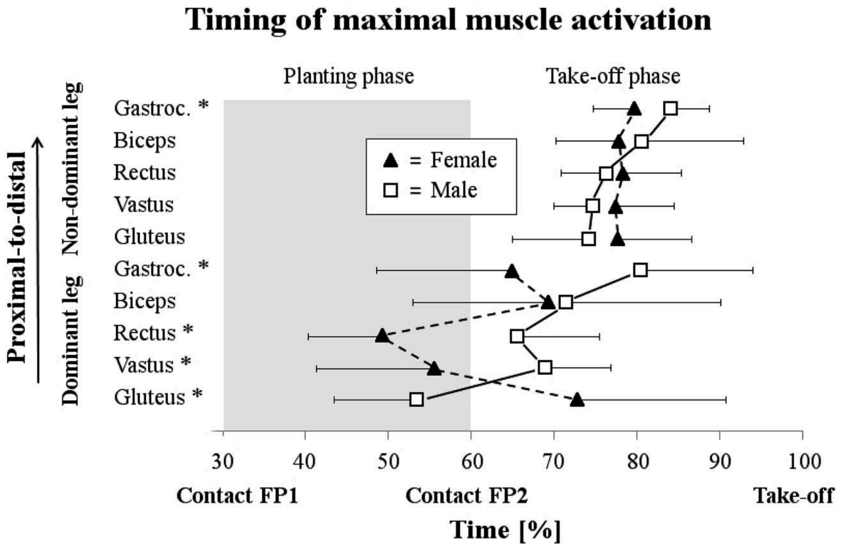

Figure 2. Mean female and male values for maximal muscle activation of lower extremity muscles of the dominant and non-dominant side.

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.

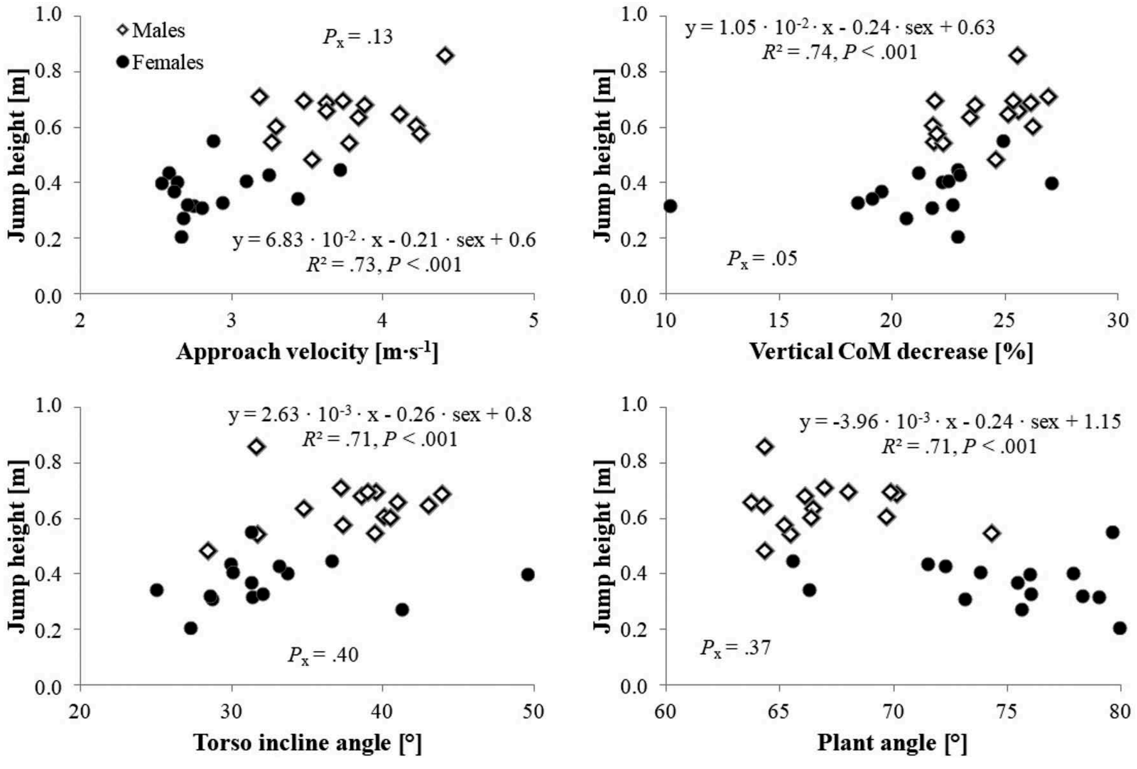

Figure 3. Multivariate regression analyses between jump height and approach velocity, vertical CoM decrease, torso incline, and plant angle, including sex as control variable.

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

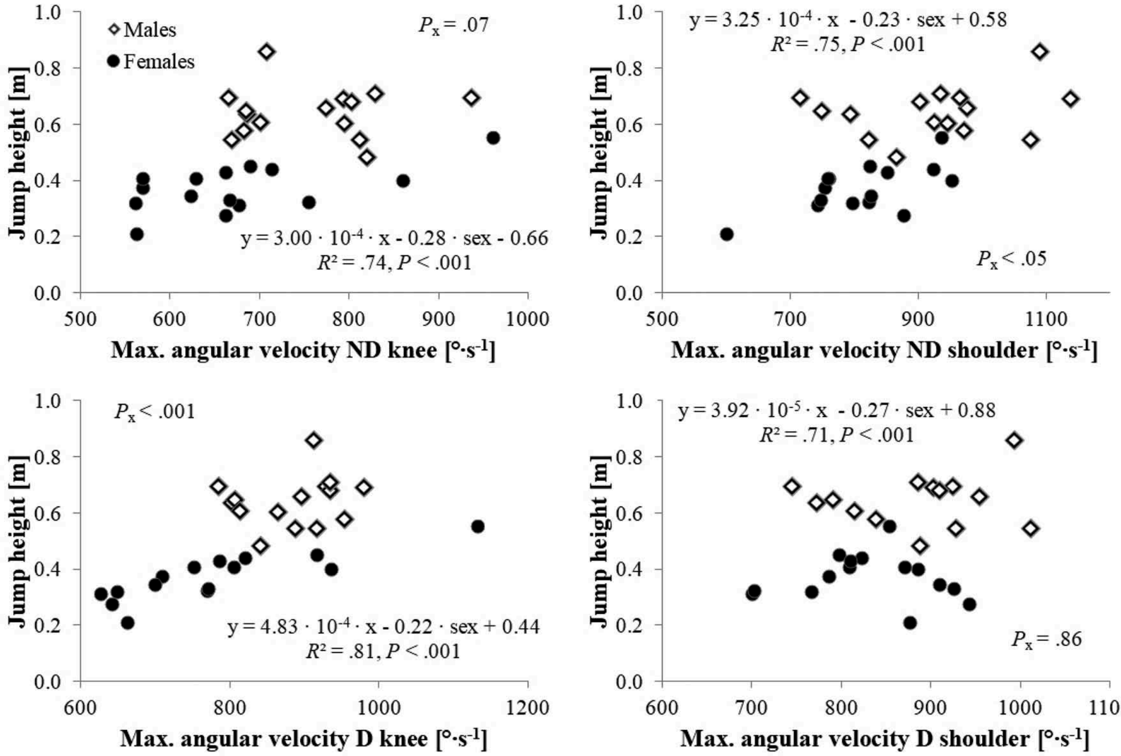

Figure 4. Multivariate regression analyses between jump height and maximal angular velocity of dominant and non-dominant knees and shoulders, including sex as control variable.

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.

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