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Movement characteristics of volleyball spike jump performance in females

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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 countermovement 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

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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 $p < 0.05$.

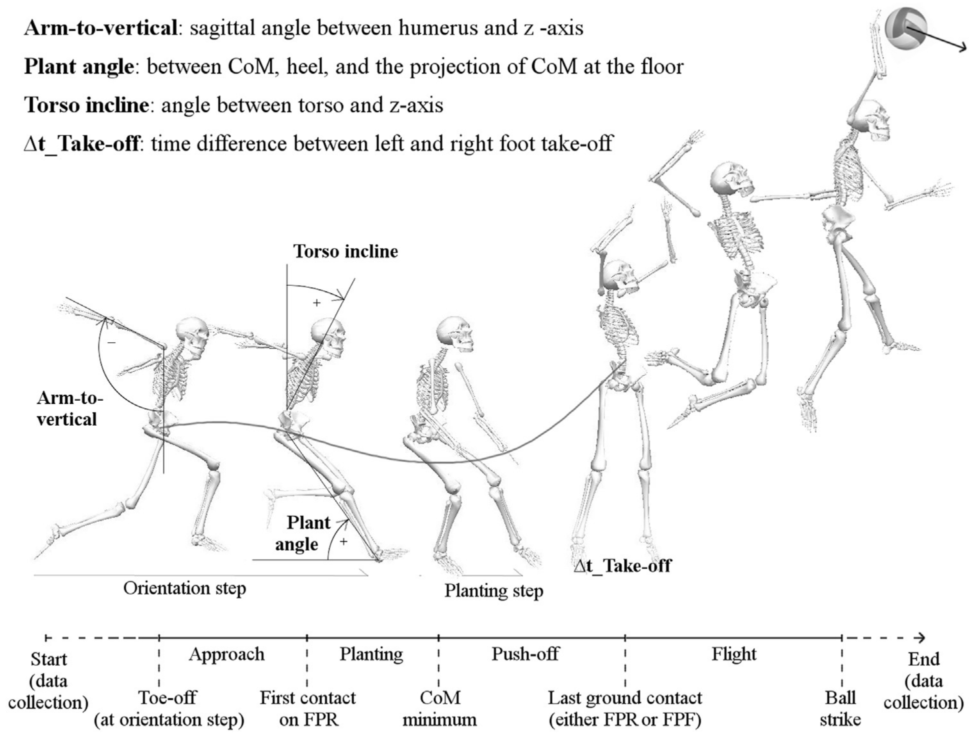

Fig. 1. Time window of analyses, phases, and variables of the volleyball spike jump. Note: FPR/F = force plate hit by rear/front leg; CoM = centre of body mass.

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 [$^\circ$ s^{-1}]	686	±	105	628	–	744	<0.01	0.75
Max. D ankle velocity [$^\circ$ s^{-1}]	763	±	165	672	–	854	<0.01	0.72
Max. ND knee velocity [$^\circ$ s^{-1}]	677	±	112	615	–	739	<0.05	0.59
Max. D knee velocity [$^\circ$ s^{-1}]	778	±	135	703	–	852	<0.001	0.85
Max. ND shoulder velocity [$^\circ$ 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 ($0.05 \le p > 0.10$) 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 = ($-0.21 + 4.49 \times 10^{-4} \times$ maximal dominant knee extension angular velocity + $0.20 \times$ 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 = ($-6.80 + 51.02 \times$ forearm length + $1.33 \times 10^{-2} \times$ maximal pelvis rotation angular velocity + $3.33 \times 10^{-3} \times$ 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.

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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.

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