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Section I – Kinesiology

Sex-Specifics in Volleyball Spike Technique, Upper-Body Strength, and Shoulder Mobility

by

Yannick Prosch [1,], Karen Zentgraf [1], Björn Wieland [1]*

This study aimed to examine sex-specific differences in the execution of key technical aspects of upper-body kinematics in the volleyball spike, such as arm cocking in the back swing, a high elbow in the forward swing, and joint angles during ball contact. In addition, upper-body strength and shoulder mobility were tested to elaborate their association with spike kinematics. A total of 77 male and female volleyball players' kinematics were analyzed via 3D-motion capturing during spiking. Strength and mobility were assessed through machine-based maximum trunk strength tests, the upper quarter Y-balance test, glenohumeral internal rotation deficit, and the shoulder mobility test of the functional movement screen. Bayesian t-tests of each variable evaluated sex differences. Multiple linear regressions were calculated separately for male and female athletes to identify predictors for spiking kinematics. Male athletes showed greater torso rotation in the backward swing and reduced shoulder mobility, while female athletes demonstrated a more vertical elbow position in the forward spike swing and superior dynamic stability in the upper quarter Y-balance test. Trunk strength and dynamic stability significantly predicted the level of arm cocking in males, while shoulder mobility was their main predictor for a high elbow in spiking. In females, a high elbow was predicted by upper-body dynamic stability. No significant predictors could be identified for kinematics during ball contact in either sex. The findings highlight sex-specific kinematic patterns in spike execution and demonstrate that strength and mobility differently enact volleyball spiking in male and female players.

Keywords: *kinematics; sport performance; performance determinants; team sports*

Introduction

The volleyball spike is one of the most decisive offensive actions in the game, directly contributing to scoring points and determining match outcomes (Challoumas and Artemiou, 2018). Regardless of the spike technique used, all can be broken down into five key phases: initiation (I), wind-up (II), arm cocking (III), arm acceleration (IV), and ball contact with follow-through (V; Giatsis and Tilp, 2022). Variations in technique are most apparent during the first two phases. In contrast, the arm cocking, arm acceleration, and ball contact phases show greater similarity across different spike styles (Giatsis and Tilp, 2022). The aim during the arm cocking phase is to position the elbow far behind the shoulder. In the arm acceleration phase, a vertical alignment of the elbow above the shoulder is advantageous to optimize the elbow extension (Oliveira et al., 2020). During ball contact, the goal is to strike the ball with the arm as fully extended as possible to reach optimal spiking height (Serrien et al., 2016). Previous research has demonstrated that these technical aspects influence spike performance, particularly ball speed after hand-ball contact. Brown et al. (2014) found that greater torso rotation, measured as the shoulder-hip angle, was associated with higher ball speed. This torso rotation corresponds to the final moment of the arm cocking phase, just before the elbow moves forward. Additionally, the degree of elbow extension at ball contact appears to be a key predictor of ball speed. Serrien et al. (2016) reported that volleyball players at higher

[1] *Department of Movement and Exercise Science, Institute of Sports Science, Goethe University Frankfurt, Frankfurt, Germany.*
* Correspondence: prosch@sport.uni-frankfurt.de

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performance levels exhibit greater elbow extension, which not only contributes to increased ball speed but also allows for a higher hitting height.

Although these technical aspects are fundamental to the volleyball spike, there are indications that women and men differ in their kinematic execution despite having the same technical guidelines. For instance, research has identified differences in jumping behavior, including jump height, jump approach, transition strategy, acceleration distances, and the use of the torso and arms (Fuchs et al., 2019). Additionally, men achieve higher arm swing speeds during the spike (Chen et al., 2011). These disparities in angular velocities in the upper limbs are largely attributed to differences in upper-body strength (Chen et al., 2011). Male elite players demonstrate significantly greater internal shoulder rotation strength, leading to a different strength ratio between internal and external rotation, as well as higher forces in elbow extension and flexion (Forthomme et al., 2005). Furthermore, men aged 25 and older display greater dynamic upper-body stability than women in their age categories (Borms and Cools, 2018). While strength differences favor male players, mobility differences suggest higher ranges of motion (ROM) for female players (Mizoguchi et al., 2022). Although these findings demonstrate sex-specific differences in technique-related variables, strength, and mobility, it remains unclear whether and how these differences translate into the execution of specific spike phases such as arm cocking, high elbow positioning, and ball contact.

Upper-body strength represents a central physical determinant of spike performance. Studies have shown that shoulder rotation strength is associated with ball speed (Forthomme et al., 2005). Beyond the shoulder musculature, trunk strength plays a critical role in force generation and transfer in overhead and striking sports (Kibler, 1998). Approximately half of the kinetic energy transferred to the hand originates from the lower limbs and the trunk (Jones and Safran, 2024). In throwing, insufficient core strength alters movement execution and may increase shoulder loading due to impaired force transfer (Burkhart et al., 2003). Given the biomechanical similarities between throwing and striking actions (Wagner et al., 2012), insufficient trunk strength may likewise influence spike mechanics in volleyball players. Common assessments of upper-body strength in overhead athletes include the upper quarter Y-balance test (Gorman et al., 2012) and maximal trunk flexion and extension strength measurements (Silva Barros et al., 2022).

In addition to strength, shoulder mobility is considered essential for efficient overhead performance. Research in volleyball has primarily examined mobility in relation to shoulder pain, focusing on glenohumeral internal rotation deficit (GIRD) and scapular control (Cook et al., 2014; Mizoguchi et al., 2022; Reeser et al., 2010b). However, mobility may also directly influence technical execution. Achieving a vertical elbow position during arm acceleration likely depends on sufficient glenohumeral and scapular motion, as demonstrated in baseball pitching (Kibler et al., 2013). To assess shoulder mobility in overhead sports, measures such as GIRD and scapular mobility using the shoulder mobility test from the functional movement screen (FMS; Cook et al., 2014) are frequently applied.

Although technique, strength, and mobility have each been investigated, they are often studied in isolation. This limits the understanding of how these elements interact during the execution of a complex, explosive movement such as the volleyball spike. As highlighted by Albaladejo-Saura et al. (2023), understanding the multifactorial contributors to performance is essential to advance performance diagnostics and individualized training. An integrated analysis of technique, strength, and mobility therefore appears necessary to better understand performance determinants in the volleyball spike. While previous research has shown sex differences in attributes such as jump approach (Fuchs et al., 2019), angular velocities (Chen et al., 2011), upper-body strength (Borms and Cools, 2018) and shoulder mobility (Mizoguchi et al., 2022), it remains unclear whether these differences translate into the execution of the volleyball spike. Therefore, the present study aimed to fill this research gap by examining whether male and female volleyball players differ in their execution of key technical aspects of the spike, specifically the arm cocking, high elbow, and ball contact phases as well as upper-body strength and shoulder mobility variables. By

analyzing the extent to which upper-body strength and shoulder mobility contribute to the spike execution in a sex-specific manner, this study sought to provide a more integrated understanding of performance determinants and may thereby contribute to the development of more targeted diagnostics and training approaches in optimizing volleyball spiking performance.

Methods

Participants

A total of 41 male (M_{age} = 18.32 ± 3.47 years) and 36 female (M_{age} = 18.69 ± 5.19 years) volleyball players (only outside and opposite hitters as well as middle blockers) were included in this study. The male and female volleyball players were competing in the 1st or 2nd German National League or were members of German national youth squads. On a single testing day, participants underwent various strength and mobility assessments as well as a kinematic analysis of their volleyball spiking.

This study was conducted following the principles of the Declaration of Helsinki and approved by the Ethics Committee of the Department of Psychology and Sports Science at the Goethe University Frankfurt, Frankfurt, Germany (approval code: 2024-11; approval date: 15 March 2024).

Design and Procedures

Kinematic Analysis of the Volleyball Spike

Before spike motion capturing occurred, all athletes completed a self-directed warm-up routine with a particular focus on shoulder activation. The aim was to prevent injuries and to ensure optimal preparation for the upcoming movements. Prior to the recorded trials, players were allowed to perform several practice spikes to familiarize themselves with the setup and determine their optimal hitting height. Measurements took place under laboratory conditions (Figures 1 and 2). Participants were instructed to hit a stationary ball, held at an individually chosen height by a member of the test team, with maximum effort. The hitting height was set individually to achieve the highest individual ball speed at maximum hitting height for each participant. The average hitting height was 2.92 m for male players and 2.60 m for female players. The approach run was straight with a maximum length of 4.5 m (Zahálka et al., 2017). The ball was hit into a small catching net positioned in front of a larger safety net. This double-net setup was designed to reduce the likelihood of a speed-accuracy trade-off, where players might lower their hitting speed in favor of precision. A radar device positioned centrally behind the nets served as a visual target for the players. The spike movement was registered using a 14-camera motion capture system (OptiTrack, Motive). A total of 21 reflective markers were attached to anatomical landmarks, following the protocol established by Seminati et al. (2015). Definitions of body segments are provided in Table 1. At the start of each measurement, a T-pose was recorded to obtain individual body measurements. Upper-arm length was defined as the distance between the acromion and the medial elbow epicondyle on the hitting arm.

The kinematic analysis focused on three key technical aspects of the spike motion: arm cocking, a high elbow, and ball contact. The arm cocking marked the start of the hitting motion. Arm cocking was defined as the moment when the medial elbow marker was furthest from the shoulder marker of the hitting arm in the sagittal plane. This distance was normalized to each participant's individual upper-arm length. An ideal value was close to 1, indicating effective torso rotation and arm loading. In the high elbow phase, the arm moved forward, and the elbow should ideally be positioned above the shoulder level. For this key technical aspect, the moment at which the medial wrist marker was furthest away from the medial elbow marker in the vertical plane was chosen. At that moment the distance between the shoulder marker and the medial elbow marker in the frontal plane was calculated and normalized to upper-arm length. A value close to 0 reflected optimal vertical elbow positioning. Ball contact was defined as the moment when the medial wrist marker was closest to the ball marker. At this point, the angle formed by the scapula marker, the medial elbow marker, and the medial wrist marker of the hitting arm was calculated. A value close to 180° indicated full elbow extension.

Measures

Maximum Upper-Body Strength

Maximum upper-body strength was

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assessed using isometric trunk flexion with the David 130 device (David Fitness & Medical ltd, Vantaa, Finland) and extension measurements with the David 110 device (David Fitness & Medical ltd, Vantaa, Finland). Participants were instructed to press against immovable resistance. They were guided to progressively increase their force over a three-second countdown from the examiner, reaching their maximal effort by the end of the countdown and maintaining it for additional three seconds. This approach ensured that peak force values were not influenced by impulsive movements. The values for flexion and extension were summed into a single score and normalized to body weight [N/kg].

Dynamic Upper-Body Stability

Dynamic upper-body stability was evaluated using the upper quarter Y-balance test (UQ-YBT) (Gorman et al., 2012). This test assesses dynamic stability of the shoulder and the core in three movement directions. Participants assumed a one-arm push-up position and were required to push the reach indicator as far as possible in the medial, inferolateral, and superolateral directions. A trial was considered invalid if the hips lost their parallel alignment with the floor, the reach indicator was pushed or leaned upon, or if the participant's hand or knee touched the ground before returning to the starting position. Before testing, arm length was measured for both sides, from the C7 vertebra to the tip of the middle finger. The reach distances in all three directions were then normalized to the arm length of the non-supportive hand. The overall UQ-YBT score was calculated by summing the reach distances in all three directions, multiplying by 100, and dividing by three times the arm length of the non-supportive hand. In this study, only the score of the non-hitting arm as the supportive arm was included in the analysis. By that, dynamic stability was assessed in a condition where the hitting arm remained free to move, as this scenario better reflects the execution of the volleyball spike

Shoulder Mobility

Shoulder mobility was evaluated using two different assessments. First, GIRD (Mizoguchi et al., 2022; Reeser et al., 2010b) was measured. Participants lay supine on the floor in a relaxed position while trained examiners assessed the maximum range of motion (ROM) for shoulder internal rotation. The achieved mobility was recorded in degrees [°] using a goniometer relative to the floor. Therefore, lower values indicated greater mobility.

Additionally, shoulder mobility scapula was assessed using the shoulder mobility test item from the FMS (Cook et al., 2014). Participants were instructed to assume a T-pose, form fists with both hands, and then to position them behind their back as close to each other as possible. Then the distance between the two fists was measured in [cm], with a smaller distance between the fists indicating greater mobility.

Statistical Analysis

All statistical operations were performed using SPSS (Version 29.0.2.0) and JASP (Version 0.19.3). The key technical aspects were calculated in MATLAB (MathWorks, 2024) using the "mocaptoolbox" developed by Burger and Toiviainen (2013). To address the first research question, whether male and female volleyball players differ in key technical aspects as well as in strength and mobility variables, Bayesian independent samples *t*-tests were conducted. Based on prior research, one-sided hypothesis tests were applied for GIRD, shoulder mobility scapula, and maximum upper-body strength, expecting male athletes to show higher values for GIRD indicating lower mobility and higher upper-body strength. For the technical aspects and dynamic upper-body stability, two-sided tests were used, as no directional assumptions were made. Bayes factors were interpreted according to the classification scheme proposed by Lee and Wagenmakers (2013).

To address the second research question, whether strength and mobility variables predicted the execution of technical aspects in a sex-specific manner, multiple linear regression analyses were conducted separately for male and female athletes. The predictor variables included in each model were selected based on their theoretical relevance to the respective technical aspect (Kibler, 1998). For example, the model for arm cocking included maximum upper-body strength and dynamic upper-body stability. The model for the high elbow phase included maximum upper-body strength, dynamic stability, glenohumeral internal rotation, and scapular mobility. The model for ball

contact included maximum upper-body strength and the superolateral reach distance of the UQ-YBT, as this variable best reflects the overhead positioning required during ball contact.

Due to the later integration of the scapular mobility assessment into the test protocol, this variable was only available for 36 male and 33 female players. Consequently, analyses involving this variable were conducted with a reduced sample size. No participant reported experiencing any pain during the diagnostics.

Results

This section presents the results of the study focusing on sex differences in technical aspects, upper-body strength and shoulder mobility (Table 2), and the contribution of upper-body strength and shoulder mobility to technical aspects in male and female players. While testing the scapula mobility, it was observed that the mobility of the hitting arm was particularly challenged when placed in the lower position. Therefore, only the distance between the fists in [cm] was included in the analysis when the hitting arm was in the lower position.

Sex Differences

Moderate evidence for sex differences was found in arm cocking ($BF_{10} = 4.571$), and very strong evidence for differences in the high elbow phase ($BF_{10} = 73.709$). In contrast, for ball contact, substantial evidence for the absence of sex differences was observed ($BF_{10} = 0.284$). Regarding strength variables, extremely strong evidence was found for higher maximum upper-body strength in males compared to females ($BF_{+0} > 100$). Additionally, very strong evidence indicated that females displayed superior dynamic upper-body stability ($BF_{10} = 50.746$). With respect to mobility, females showed better values in both GIRD ($BF_{+0} = 47.531$) and the shoulder mobility scapula ($BF_{+0} = 0.830$). However, only GIRD demonstrated very strong evidence for sex difference.

Influence of Strength and Mobility on Technique

Males

Among male athletes, the technical aspects, i.e., arm cocking (adjusted $R^2 = 0.205$; $p = 0.005$) and the high elbow (adjusted $R^2 = 0.440$; $p < 0.001$) were significantly predicted by the selected variables. For arm cocking, maximum upper-body strength ($\beta = 0.369$; $p = 0.013$) and dynamic upper-body stability ($\beta = 0.364$; $p = 0.014$) emerged as significant predictors. For the high elbow, the shoulder mobility scapula ($\beta = 0.604$; $p < 0.001$) and dynamic upper-body stability ($\beta = 0.321$; $p = 0.018$) were found to be significant. In contrast, ball contact (adjusted $R^2 = 0.024$; $p = 0.237$) was not significantly predicted by any of the variables ($p > 0.050$). A visual representation can be seen in Figure 4.

Females

In contrast, among female athletes, only the high elbow could be significantly predicted (adjusted $R^2 = 0.323$; $p = 0.004$). Within this model, dynamic upper-body stability emerged as a significant predictor ($\beta = -0.420$; $p = 0.018$). Neither arm cocking (adjusted $R^2 = -0.055$; $p = 0.915$) nor ball contact (adjusted $R^2 = -0.015$; $p = 0.483$) could be significantly explained by any of the included strength or mobility variables ($p > 0.050$) (Figure 4).

Table 1. Marker positions and definitions of body segments.

Body segment	Marker
Hip	Left and right anterior superior iliac spine (ASIS), as well as the lowest possible point of the lumbar spine
Thorax	Xiphoid process, jugular notch, C7, and T10
Shoulder	Left and right acromion, superior margin of the scapula of the hitting arm
Upper arm	Three markers on the lateral side of the hitting upper arm (technical reference frame) at three different heights, dividing the upper arm into three parts. The middle marker placed further lateral than the upper and lower markers
Elbow	Medial and lateral epicondyle
Forearm	Midpoint of the forearm (lateral side)
Wrist/Hand	Radial and ulnar styloid process, third metacarpus
Non-hitting arm	Medial epicondyle and radial styloid process

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Table 2. Means ± standard deviations for each technical aspect, strength and mobility variable for male and female volleyball players.

Variable	Male	Female	Bayes Factor
Arm cocking [au]	0.81 ± 0.12	0.73 ± 0.16	4.571
High elbow [au]	0.54 ± 0.13	0.38 ± 0.23	73.709
Ball contact [°]	139.14 ± 8.88	137.88 ± 7.98	0.284
Maximum upper-body strength [N/kg]	5.42 ± 0.67	4.60 ± 0.64	>100
Dynamic upper-body stability [au]	85.37 ± 7.79	91.81 ± 7.84	50.746
Internal rotation [°]	40.39 ± 9.38	32.92 ± 10.30	47.531
Shoulder mobility scapula [cm]	16.75 ± 7.30	14.73 ± 6.15	0.830

Figure 1. Setup of the motion capture system.

Figure 2. POV from the volleyball players at the start of the spike.

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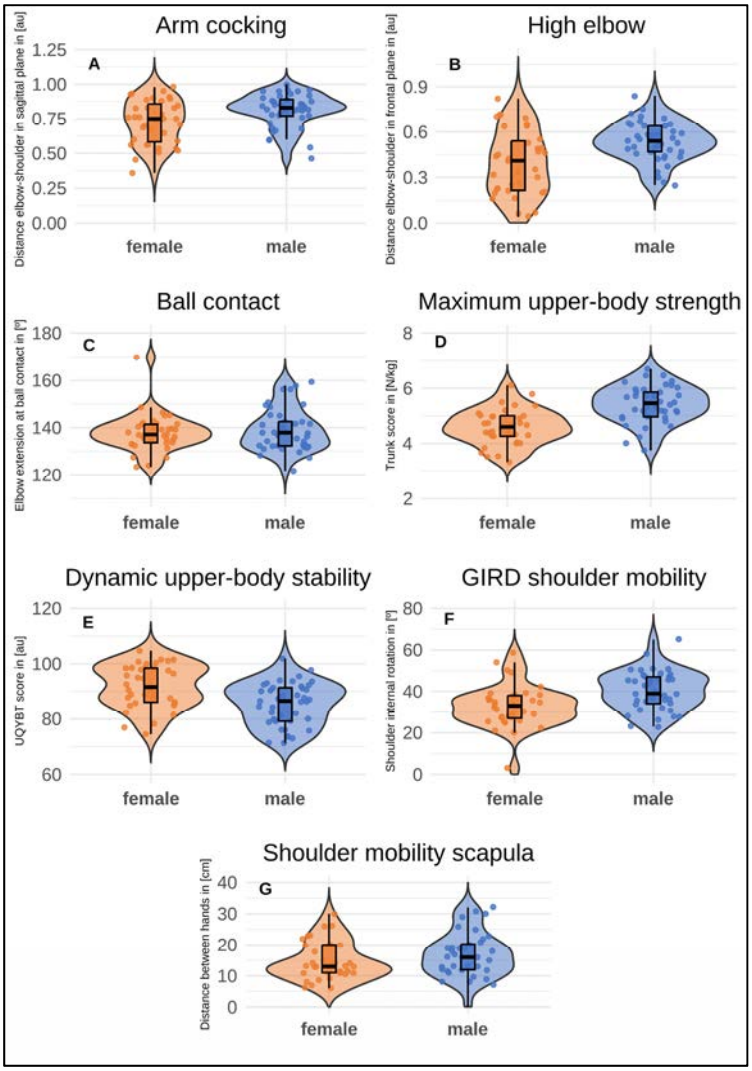

Figure 3. Scatterplot with the violin plot and the boxplot of each key technical aspect, strength and mobility variable for male and female volleyball players.

This figure shows the sex differences between female (orange) and male (blue) volleyball players in arm cocking (A), high elbow (B), ball contact (C), maximum upper-body strength (D), dynamic upper-body stability (E), GIRD shoulder mobility (F), and shoulder mobility scapula (G)

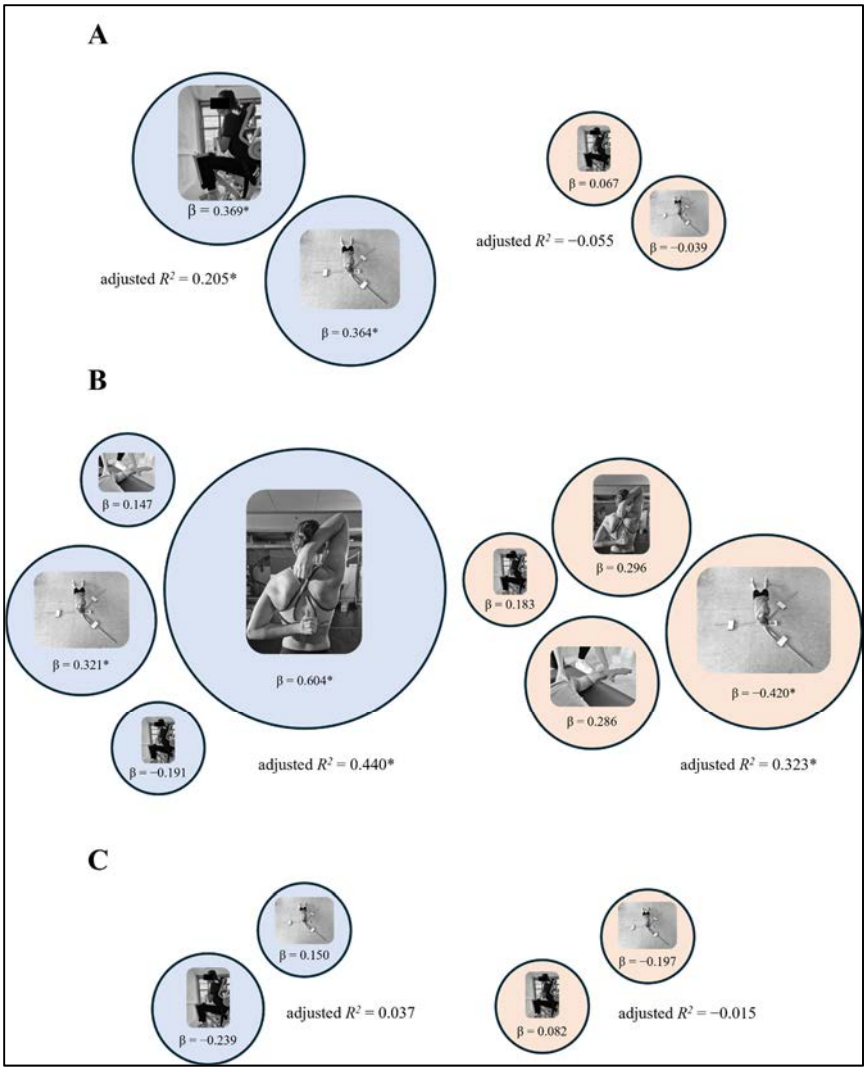

Figure 4. Representation of the multiple linear regressions for each analysis separated for male and female volleyball players.

This figure shows the different results of the regressions for male (blue) and female (orange) in arm cocking (A), high elbow (B) and ball contact (C), as well as the size of the influence of the predictors based on the size of the circles ($p < 0.05$). To ensure adequate representation of small standardized beta values, a minimum circle size was defined*

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Discussion

This study aimed to investigate sex-based differences in the kinematics of the volleyball spike and to assess how upper-body strength and shoulder mobility contribute to spike execution. Specifically, we examined whether male and female players differed in the execution of key technical aspects of the volleyball spike and whether physical characteristics such as maximal upper-body strength and shoulder range of motion would predict these execution patterns. We revealed relevant differences between male and female volleyball players in technical execution, strength, and mobility variables. Male players showed greater torso rotation during arm cocking, whereas female players positioned their elbow more vertically above the shoulder in the high elbow phase. The differences in spike execution, especially in arm cocking, may be linked to known sex-specific variations in throwing mechanics. Ehl et al. (2005) observed that among German adolescents, the throwing motion differed during the backswing phase and in the involvement of the humerus and the forearm between boys and girls. Male participants displayed a more pronounced backswing during throwing, which mirrors the findings of this study. The backswing in throwing corresponds to the arm cocking phase in the spike, during which men showed greater shoulder and arm rotation. Similarly to arm cocking, sex differences were found in the high elbow, where female players achieved a more vertically aligned elbow over the shoulder. These distinctions may be attributed to differences in shoulder mobility between the sexes. Indeed, shoulder mobility, measured using the FMS (with the hitting arm in the lower position), was significantly correlated with high elbow positioning in both male and female players (Pearson $r_{male} = 0.594$, $p < 0.001$; Pearson $r_{female} = 0.470$, $p = 0.006$). No sex-based differences were observed in the final technical aspect, i.e., ball contact. Both male and female athletes contacted the ball with a similarly extended arm. The degree of extension (male: 139.14 ± 8.88; female: 137.88 ± 7.98) in this cohort aligns with values reported in previous studies, accounting for methodological differences in how elbow angles are calculated (Reeser et al., 2010a; Serrien et al., 2016).

Additionally, men demonstrated higher maximum upper-body strength, while women exhibited superior dynamic upper-body stability and greater shoulder mobility, particularly in internal rotation ROM. Differences in strength between male and female volleyball players have previously been reported for specific variables; however, differences in maximum upper-body strength have not been thoroughly examined. Despite the athletes in this study being of similar age, we hypothesized that male players would exhibit higher upper-body strength due to their generally greater muscle mass. To enable meaningful comparisons within and between groups, strength values were normalized to individual body weight, an approach commonly used in overhead sports research (Hurd et al., 2011). Even after normalization, male players demonstrated significantly higher maximum upper-body strength, indicating superior absolute and relative upper-body strength. In contrast, female players achieved higher reach distances on the non-dominant side in the UQ-YBT. This finding differs from Borms and Cools (2018) who reported significantly higher UQ-YBT values for male athletes. However, their results showed sex differences only in age groups above 26 years, with no significant differences in the 15–18 age group, similar to our cohort's average age of 18. This may explain the different outcomes. Another explanation could be the reduced mobility of the hitting shoulder in men. As our data show, men display reduced mobility compared to women. Since we analyzed the non-hitting arm as the supporting arm, the reduced mobility of the hitting arm may be a factor in why men achieved lower scores on the dynamic upper-body stability. In addition, it should be mentioned that male volleyball players underperformed compared to the reference values of Borms and Cools (2018). Regarding female volleyball players, they exhibited superior performance compared to the reference values of Borms and Cools (2018). The sex-specific differences in shoulder mobility described in the literature were also confirmed in this study. Female volleyball players showed greater mobility in both internal shoulder rotation and the shoulder mobility scapula. In general, volleyball players of both sexes exhibit reduced internal rotation in the hitting shoulder compared to the non-hitting side (Challoumas et al., 2016; Harput et al., 2016; Mizoguchi et al., 2022; Wang et al., 2004), a finding that was also evident in our

cohort ($male_{hit}$ = 40.39°; $male_{nonhit}$ = 29.98°; $female_{hit}$ = 32.92°; $female_{nonhit}$ = 29.64°). However, this reduced range of motion does not appear to result from painful limitations, but rather from functional adaptations of the joint structures and surrounding musculature due to the high number of spike repetitions (Challoumas et al., 2016).

Sex-specific differences were observed in upper-body strength, shoulder mobility, and technical aspects. Furthermore, the study aimed to determine whether upper-body strength and shoulder mobility influence the execution of technical aspects in a sex-specific manner. Among male athletes, maximum upper-body strength and dynamic upper-body stability emerged as important prerequisites for achieving a pronounced torso rotation during arm cocking. In contrast, different results were found for female athletes. No significant predictors were identified for the arm cocking phase. For the high elbow, shoulder mobility appeared to be the limiting factor for positioning the elbow vertically above the shoulder for male athletes. For female players, in contrast to the male players, the mobility of the shoulders seemed to be a weaker predictor in achieving the vertical elbow position, which may be attributed to the generally higher levels of both shoulder mobility and dynamic stability observed in the female cohort. However, the execution of the high elbow was significantly influenced by dynamic upper-body stability in female volleyball players. Female volleyball players with high dynamic upper-body stability show a lower distance between the elbow and the shoulder in the frontal plane. These results underscore the importance of neuromuscular training of the entire kinetic chain to optimize volleyball spike execution (Kibler, 1998) for both male and female volleyball players. It has also been shown in baseball players that the angular velocity of the arm increases when the velocity of the trunk increases (Hirashima et al., 2008). It is important to note that no predictors for ball contact were found for both male and female volleyball players. Maximum upper-body strength and dynamic upper-body stability in the superolateral direction therefore appear to have no influence on elbow extension at ball contact.

This study provides a unique and integrated perspective on the kinematics of the volleyball spike by examining sex-specific differences in both the execution of key technical aspects and their physical determinants. Unlike previous research that investigated technique, strength, and mobility in isolation, our findings highlight the interplay between these components and how they differ between male and female athletes. Notably, we show that maximum upper-body strength and dynamic upper-body stability play a decisive role in spike execution, particularly in generating torso rotation during the arm cocking phase for male players. For female athletes, dynamic upper-body stability emerges as a key factor in achieving an optimal high elbow position, while shoulder mobility appears to play a lesser role, likely due to generally higher baseline levels.

These findings not only deepen our understanding of performance-relevant kinematics in volleyball, but also offer direct implications for individualized training approaches: trunk and dynamic stability training should be tailored by sex and by technical focus.

Conclusions

In summary, male and female volleyball players differ in the execution of the spike. While men wind up further in the arm cocking, women position the elbow more vertically above the shoulder in the high elbow. Men show significantly higher maximum upper-body strength, while women have higher dynamic upper-body stability and higher shoulder mobility. In male players, maximum upper-body strength and dynamic upper-body stability appear to be important for the execution of arm cocking and shoulder mobility is a limiting factor for the high elbow. In women, on the other hand, dynamic upper-body stability appears to be important for the high elbow. Technical training for female players should place particular emphasis on the arm cocking, as this movement tends to be less pronounced. Early exposure to throwing and spiking mechanics may help female players to establish key motor patterns from a young age. For male players, a strong core musculature and dynamic upper-body stability appear to be essential for performing a well-executed arm cocking phase. Additionally, improving shoulder mobility should be a training focus to enhance high elbow positioning and to better exploit the stretch-shortening cycle during the acceleration phase.

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ORCID iD:

Yannick Prosch: https://orcid.org/0009-0002-9674-5893

Karen Zentgraf: https://orcid.org/0000-0002-1118-4015

Björn Wieland: https://orcid.org/0000-0003-2287-035X

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Institutional Review Board Statement: This study was conducted following the principles of the Declaration of Helsinki and approved by the Ethics Committee of the Department of Psychology and Sports Science at the Goethe University Frankfurt, Frankfurt, Germany (approval code: 2024-11; approval date: 15 March 2024).

Informed Consent: Informed consent was obtained from all participants included in the study.

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