Ball Speed Predictors in One-Legged Attacks in Female Volleyball Players

Tina Stefanovic

Master of Science in Kinesiology

Point Loma Nazarene University

Abstract

Previous literature in volleyball biomechanics highlighted jump height and ball speed as key determinants for the success of regular spikes. To further current research and provide athletes and coaches with direct parameters for proper execution of more complex volleyball attacks, ball speed predictors of a slide attack were investigated. Healthy collegiate female volleyball players (middle blockers, pin hitters), actively participating in volleyball were recruited. After a warm-up, 3 successful slide attacks per participant were recorded using an 8-camera motion capture system, while a radar gun was used to measure the ball speed upon contact. The trial with the fastest ball speed was selected for further analysis, where COM approach speed, maximum velocity of pelvis and torso in the arm cocking phase, and maximum velocity of torso, shoulder, and elbow during the arm acceleration phase were calculated. It was hypothesized that a combination of these variables will help reliably predict the ball speed in slide attacks. Although not statistically significant, the findings indicate that peak torso velocity in the arm cocking phase and peak shoulder and peak elbow velocities in the arm acceleration phase are important contributors to the ball speed in slide attacks. Still, the most influential contributor to the ball speed is peak torso velocity during the arm cocking phase.

Keywords: ball speed, volleyball, kinematics, injury prevention, performance

Ball Speed Predictors in One-Legged Attacks in Female Volleyball Players

Volleyball is considered to be one of the most popular sports in the world among both men and women, due to minimal equipment requirements, wide age spectrum, and ability to play indoors and outdoors (James, Kelly, & Beckman, 2014). Playing volleyball at a highly competitive level requires excellence in various skills such as setting, blocking, serving, serve receiving, and attacking. However, attacking is the single most important volleyball skill which directly impacts the successfulness of matches on a high level of competition and where ball speeds approach 28 m/s (Palao, Santos, & Ureña, 2004; Reeser et al., 2010). A previous research study showed that an elite volleyball player, who practices between 16 and 20 hours per week, executes approximately 40,000 spikes during one season (Kugler et al., 1996). As shoulder pain and discomfort account for 8-20% of all volleyball-related injuries, the high number of repetitions and power required for a successful volleyball swing increase the risk of a potential shoulder injury (Reeser et al., 2010). This is the case especially for volleyball players who are involved in the offense aspect of matches, as they are more likely to develop shoulder-related injuries.

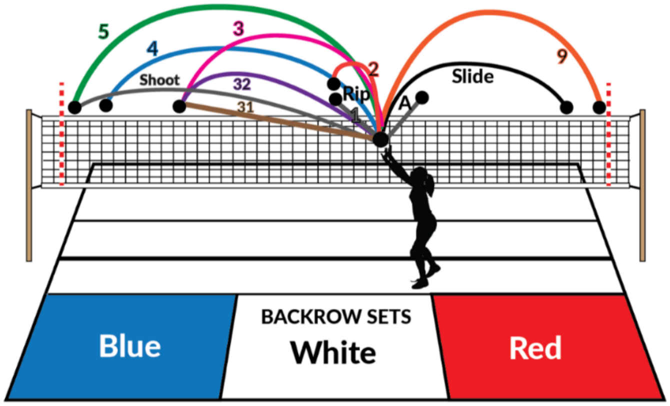

Figure 1. Different types of volleyball attacks and zones. (2020). Retrieved from https://digsvbc.com/at-home-volleyball-training.

Volleyball spike motion can be divided into four phases – approach, arm cocking, acceleration, and follow-through (Reeser et al., 2010). The different types of spikes and approach-type movements can be slow-paced, fast-paced, one-legged, two-legged, front-row, and back-row (Figure 1). In a regular volleyball game, middle blockers have the second highest number of hitting attempts with an average of 4.51 attacks per set (Hurd et al., 2009). Quicker and more explosive attacks are harder to block and dig and are, thus, highly favorable in volleyball. For middle blockers, the most successful attack is a “slide”, where the hitter runs parallel to the net behind the setter, jumps off of one leg, and drifts (Figure 2). Due to the complexity of the motion, approaches, and techniques used in different attacks, researchers only recently started investigating kinetics and kinematics behind the basic volleyball swing. Still, very little is known about the biomechanical characteristics of more complex attacks, such as slides, and their relationship with the ball speed.

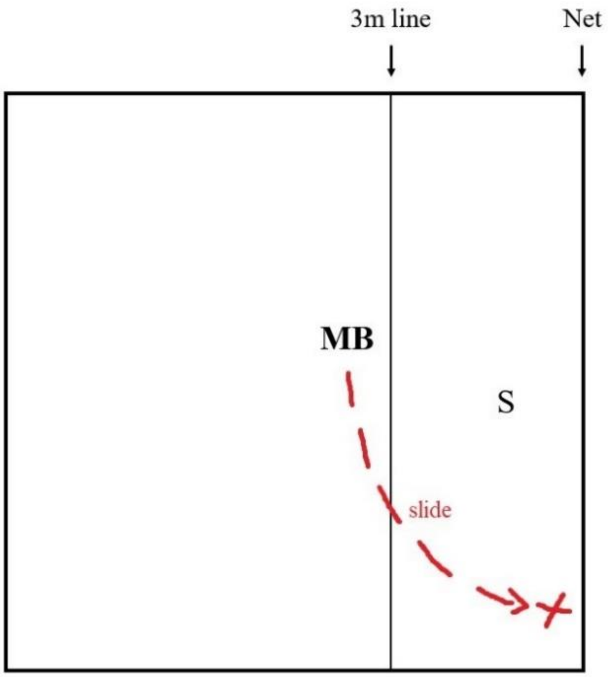

Figure 2. Slide attack zone in volleyball.

Shoulder injuries have serious short-term and long-term effects on athletes' mental health and sports performance. As rehab time and average time loss from volleyball are the longest for shoulder-related injuries when compared to any other type of injury, a clinical need for understanding the biomechanics behind properly executed one-legged swings exists (Reeser et al., 2010). Additional research in a volleyball setting is needed in order to give guidance to coaches and players on predictors of successful attacks with the goal of maximizing players' performance while reducing the risk of a shoulder injury.

Review of Literature

Proximal-to-Distal Sequence in Volleyball

Overarm movements are essential to different sports, such as baseball, handball, tennis, and volleyball. Even though the overarm techniques and their ranges of motion vary depending on the sport requirements, research has revealed that these sports show an equal order in the proximal-to-distal sequence of the maximal angular velocities of the pelvis, trunk, and dominant arm angles (Wagner et al., 2012). Proximal-to-distal sequence represents the pattern of muscle activation which allows the transfer of momentum and energy from proximal to distal segments of the body (Serrien, Goossens, & Baeyens, 2018). For handball, tennis, and volleyball, pelvis rotation is followed by trunk backward rotation, trunk flexion, shoulder hyperextension, and elbow flexion in the early cocking phase and by the trunk hyperextension at the end of the cocking phase. Similar proximal-to-distal sequence can be noted for baseball pitching as well, with the most prevalent order of joints being pelvis, trunk, arm, hand, forearm (Scarborough et al., 2018).

Serrien, Goossens, and Baeyens (2018) looked at the effects of gender and growth on proximal-to-distal sequencing and coordination variability in the volleyball spike of elite youth players. The longitudinal study observed boys and girls in late puberty before, during, and after a two-year period. Although performance increased and performance variability decreased over time, these changes were not statistically correlated with growth. The typical proximal-to-distal sequence described in the previous literature, with elbow extension before shoulder internal rotation, was present in the study sample. However, the initiation of elbow extension before shoulder internal rotation was present in girls, which did not align with the previously published evidence by Marshall and Elliott (2000). This study was one of the first studies to confirm that volleyball players display the typical proximal-to-distal sequence behavior and show that the effects of gender play an important role in sequencing.

Potential Parallels Between Baseball and Volleyball Research

In baseball pitching, according to Aguinaldo and Escamilla (2019), the flow of mechanical energy through the kinetic chain that follows the proximal-to-distal sequence can define efficient throwing mechanics. This flow of mechanical energy is explained by the "summation of speed principle" which states that as one segment of the body reaches its peak velocity, it will initiate a rotation of another segment proximal to it. Aguinaldo and Escamilla (2019) attempted to examine how segmental energy flow (power) influences elbow valgus torque and ball speed in professional and high school pitchers. The study investigated kinematics of the pelvis, trunk, shoulder, and elbow joints as the most relevant joints in the sequential body motion. Results of the study suggest that trunk rotational torque is the primary source of power production for both ball velocity and elbow valgus torque, due to the trunk's large segmental mass (Aguinaldo & Escamilla, 2019). These findings provided guidance to coaches and players on the training methods for maximizing pitching performance while reducing the injury risk. Although studies on the proximal-to-distal sequence in volleyball spike exist and show consistency between volleyball and other overarm sports, the impacts of mechanical energy flow and segmental power analysis previously described for baseball pitching are still unknown for volleyball (Wagner et al., 2012). Research is lacking in investigating variables that are prerequisites for understanding key performance factors in female volleyball, especially in different types of volleyball attacks and approaches. Thus, using findings in baseball pitching as a foundation on which research in volleyball mechanics can be furthered is warranted.

Volleyball Spike Performance Determinants

Jump height and ball velocity are two main performance determinants for the success of spikes in volleyball (Forthomme et al., 2005; Fuchs et al., 2021). As such, multiple studies were done on the topic of optimal jump mechanics in male volleyball players. The importance of ground reaction forces, approach speeds, depth of the countermovement, knee angles, and arm swing were determined to be the most important factors in defining the optimal jump mechanics (Bobbert & Schenau, 1988; Wagner et al., 2009). Systematic reviews have found strong indications that the spike jump height depends on the velocity of the center of mass (Oliveira et al., 2020). For the ball velocity of a regular spike in volleyball, Wagner et al. (2012) highlighted the relevance of pelvic and torso momentum, the transition into angular velocities in the shoulder internal rotation and flexion, as well as elbow extension. Taking these factors into consideration, along with the lack of reports for female volleyball player performance, Fuchs et al. (2019) attempted to investigate the relationship between movement characteristics in a basic female volleyball spike jump and to determine the most relevant predictors of jump height and ball velocity. While jump height and ball velocity were the main variables of interest, range of motion, maximal angular velocities, and forces were computed for ankles, knees, hips, and shoulders. Ten out of 42 variables observed correlated with and significantly predicted the jump height, however, none of the 22 correlated with the ball velocity. These results were not consistent with the results from Coleman, Benham, and Northcott's study that found a significant correlation between post-impact ball speed and maximum right humerus angular velocity in volleyball spikes (1993). The study from Fuchs et al. (2019) was the only publication that attempted to predict the ball speed using different biomechanical factors and it was not without various limitations. Although volleyball spikes can have different techniques associated with different joint kinematics, spike techniques and their consistency were not taken into consideration in this study (Seminati et al., 2015). In addition, the sample consisted of only one team with all volleyball positions included. However, it is important to note that defensive players may not be as efficient with their attacking techniques as offensive players. As a result, additional research is needed to assess whether the ball speed of more complex attacks in volleyball, such as "slide" attacks, can be predicted using biomechanical factors while focusing on consistent spiking techniques among offensive volleyball players solely.

Therefore, the purpose of this study was to investigate the predictors of ball speed in one-legged slide attacks in female volleyball players and provide athletes and coaches with direct parameters for successful spiking techniques. By relying on previous findings, it was hypothesized that the COM approach speed, maximum velocity of pelvis and torso in the arm cocking phase, and maximum velocity of torso, shoulder, and elbow during the arm acceleration phase, will be reliable predictors of the ball speed in slide attacks.

Methods

Participants

The slide attack motion analysis of a total of 8 female volleyball players was included in this study. Of these 8 players, all of whom were right-handed, 7 were NCAA DII collegiate players and 1 was a collegiate varsity volleyball player (Table 1). At the time of the study, all of the players were actively participating in volleyball, served as hitters on their volleyball teams holding either a middle blocker, outside hitter, or right-side hitter position, and were proficient in performing slide attacks. The data collection occurred during the COVID-19 modified spring season for the NCAA DII players (N = 7), where they had 6 weeks of competition but were limited to 20 hours of countable athletically related activities per the NCAA legislation (NCAA, 2020). Exclusion criteria included having a history of surgery within the 6 months prior to the start of the study as well as active injury that could inhibit their volleyball performance.

As a part of the informed consent process, all participants who met the inclusion criteria were provided with a complete description of the study and were required to sign an informed consent form. A copy of the consent form was given to all participants and the voluntary nature of the study, option to discontinue participation, and ability to ask questions at any point were addressed. The study received an approval from the Point Loma Nazarene University's Institutional Review Board (IRB), which ensured full protection of the participants' rights and welfare.

Table 1

Participant Characteristics (N = 8).

Characteristic	Mean and SD
Age, y	19.63 ± 1.06
Height, cm	178.59 ± 6.18
Weight, kg	68.04 ± 3.64

Volleyball experience, y	8.75 ± 2.60
All sport-related activities/week, h	13.75 ± 3.54
Volleyball-related activities/week, h	10.88 ± 3.18

Instrumentation

For the purposes of collecting spatiotemporal, kinetic, and kinematic data, an 8-camera motion capture system (*Kestrel*, Motion Analysis Corp., Santa Rosa, CA) integrated with the *Cortex* motion capture software (C-Motion, Germantown, MD) was used. The sampling rate of 240 Hz was reported in previous research and, thus, was implemented in this study as well (Reeser et al., 2010). A Sport 2 radar gun was used to measure the ball speed upon contact (Stalker Sport, Richardson, TX).

Protocol and Testing

The entire data collection was performed in the Golden Gymnasium at Point Loma Nazarene University. The net was adjusted to the women's regular net height (2.24m) and the motion capture cameras were set up around the volleyball court (Figure 3). First, the motion capture system was calibrated using the L-frame, a process also known as "seed calibration". For this procedure, the L-frame containing four reflective markers was placed in the center of the camera view. Next, the system was calibrated using "wand calibration". An investigator walked around the camera capture volume waving the wand in multiple directions to ensure maximal coverage by all eight cameras. This allowed the reconstruction of the 3D locations based on 2D images from the motion capture cameras and correction of the lens distortion. To verify successful calibration, residuals of 0.38 ± 0.23 were compared to the following criteria: $r > 1.00$: bad calibration, $r < 1.00$: good calibration, and $r < 0.50$: excellent calibration. The study investigators stayed at their designated stations all throughout the data collection to ensure low variability between the warm-up, marker placement, and data collection procedures.

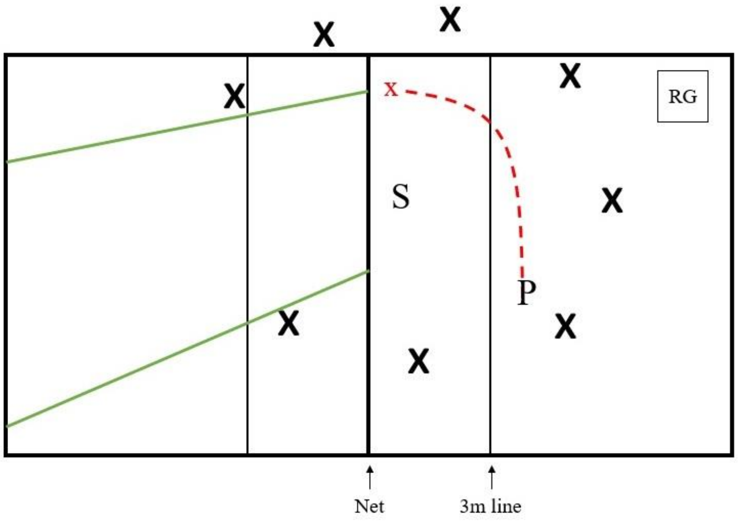

Figure 3. Motion capture setup and court labeling. X – camera position, P – participant's starting point, S – setter location, RG – radar gun position, red dotted line – slide approach, green solid line – target area.

Each athlete was instructed to wear tight-fitting clothes on the day of data collection for the purposes of marker placement (sports bra, spandex). The participants showed up in self-selected pairs in 30-minute increments to minimize their downtime and ensure maximal performance. Upon their arrival, all participants were required to sign the informed consent form and fill out a brief questionnaire containing a set of standard questions regarding age, height, weight, and volleyball experience. Next, the participants were led through a 10-minute dynamic warm-up (Table 2) and a 10-minute volleyball-specific warm-up. The dynamic warm-up protocol contained a variety of movements through the full range of motion and was created to increase the athletes' blood flow, decrease the risk of injury, and prepare their muscles for volleyball-specific tasks. The volleyball warm-up was designed to prepare the athletes' hitting arm and it consisted of pepper-style exercises according to the participants' normal routines.

Table 2

Ten-minute Dynamic Warm-up Protocol.

Exercise	Purpose
Run to the net and end line (x3)	Initializes the warm-up protocol and increases the heart rate.
Overhead shuffle	Dynamic movement that helps prepare for volleyball-specific tasks.
High knee karaoke	Prepares the body for explosive movements.
Split squat with a twist	Allows stretching of the hips, hamstrings, and back.
Knee pulls	Helps stretch hip flexors while working on balance.
Inchworm to push up (halfway) into the world's greatest stretch	Activates the upper extremity and core muscles and stretches the lower body.
A-skips	Activates hip flexors while emphasizing coordination and efficient foot strikes.
Butt kicks	Warms up the quads and increases the heart rate.
Hip mobility on the ground	Helps open up the hips.

Fast feet slow hands into a sprint to the net, 5 split squats, and 5 squat jumps	Prepares the body for explosive movements.
Arm circles/dominant arm stretching	Prepares the hitting arm for hitting motions.

Using the PitchTrak marker set, 40 passive reflective markers (1.4cm diameter) were placed on various upper and lower body landmarks to estimate joint locations and bone segments, as done in previous baseball pitching research (Aguinaldo, Buttermore, & Chambers, 2007). The anatomical landmarks were as follows: (1) head: top, rear, front, (2) torso: left and right acromion, left and right medial and inferior scapula, right clavicle, (3) pelvis: left and right ASIS, sacrum, (4) upper extremity: left and right lateral and medial epicondyle of humerus, forearm ulna, wrist radius and ulna, and dominant hand, (5) lower extremity: left and right thigh, lateral and medial knee, shank, lateral and medial ankle, heel, and toe. The marker placement was conducted upon successful completion of the warm-up protocol and, where possible, the markers were attached directly to the participants' skin to maximize location accuracy during dynamic trials.

As the first step in data collection, four static trials were collected per participant to create a template for data processing. Prior to collecting the dynamic trials, each participant was allowed to practice running slide attacks to familiarize themselves with the motion capture set-up as well as get comfortable with the marker placement. Once the participants felt ready, they each performed slide attacks off of a set until three successful trials were recorded per participant. An investigator stood behind the participants to collect the ball speed upon contact using a Sport 2 radar gun (Stalker Sport, Richardson, TX) that was held in line with their hitting arm. An attack was considered successful if: (1) the ball was in bounds and within the defined cross-court zone,

(2) both the participant and the setter agreed the attack was successful, and (3) the participant confirmed maximum spike power was used. In order to ensure low variability between sets, a high-level setter from the same volleyball team aided in the data collection for all participants. Although all three successful trials were analyzed using marker identification techniques that incorporated a fourth-order zero-lag Butterworth filter at a cutoff frequency of 18 Hz, only the trial with the fastest ball speed was selected for further analysis.

Data Extraction

The joint kinetics and kinematics of each participant's slide attack motion were estimated and scaled to each participant by the global locations of the motion-captured markers. For the purposes of this study, only the kinematics of the pelvis, torso, shoulder, and elbow joints were analyzed. The four phases of the slide attack were defined as approach (start to takeoff), arm cocking (takeoff to MER), arm acceleration (MER to impact), and follow-through (impact to landing), as done in previous studies, where MER stands for the maximum external rotation of the shoulder (Reeser et al., 2010). Ball speed was the primary variable of interest and it was recorded using a radar gun. COM approach speed during the approach phase, maximum velocity of pelvis and torso in the arm cocking phase, and maximum velocity of the torso, shoulder IR, and elbow extension during the arm acceleration phase were analyzed as kinematic variables. Negative values for the peak torso, shoulder, and elbow velocity were omitted in the results section, however, peak torso velocity had a leftward rotation or rotation towards the ball, peak shoulder velocity had the direction of internal rotation, and peak elbow velocity had the direction of elbow extension. All kinematic computations were performed using Visual 3D software (C-Motion Inc., Germantown, MD).

Statistical Analysis

R (Version 4.0.2; R Core Team, 2020) and RStudio (Version 1.3.1093; RStudio, 2020) were used for the purposes of statistical analysis. The ball speed was the continuous dependent variable, whereas the COM approach speed and maximum velocities of different joints during selected phases were continuous independent variables. Summary statistics, including mean and standard deviation, were calculated for the participants' age, height, weight, years of volleyball experience, total sport activity hours, and volleyball-only activity hours (Table 1). In addition, means and standard deviation of ball speed and all maximum velocities of segments of interest during select phases were calculated for all participants (Table 3). The independence of observations was confirmed using the Durbin-Watson statistic. Next, the linear relationship between the dependent and each of the independent variables was assessed using the Pearson product-moment correlation to ensure homoscedasticity, normal distribution, and absence of any significant outliers. Finally, a multiple stepwise regression was done at an *a priori* significance level of .05 to determine an equation with the best fit that successfully predicts the ball speed using a linear combination of the aforementioned biomechanical parameters.

Results

Table 3 lists peak velocities of different segments and kinematic variables during select phases. Maximum COM approach speed between start and takeoff, when averaged between the participants, was 4.2 ± 0.5 m/s, while the average ball speed upon impact was 16.0 ± 1.1 m/s. During the arm cocking phase, kinematic variables of interest were pelvis and torso angular velocities, which peaked at 379.5 ± 98.1 deg/s and 65.8 ± 65.3 deg/s, respectively. For the arm acceleration phase, torso, shoulder, and elbow peak angular velocities, when averaged between the participants, were 408.1 ± 39.0 deg/s, 1014.3 ± 472.8 deg/s, and 184.5 ± 170.6 deg/s, respectively. Figures 4, 5, and 6 illustrate the time series progression of the torso, shoulder, and elbow angular velocities, respectively, throughout the arm cocking and arm acceleration phases, between takeoff and impact.

Table 3

Maximum Values of Kinematic Parameters (N = 8). Data are shown as mean ± SD. AC – arm cocking phase, AA – arm acceleration phase.

Variable	Mean ± SD
Ball Speed, m/s	16.02 ± 1.12
COM Approach Speed, m/s	4.16 ± 0.51
Peak Pelvis Velocity (AC), deg/s	379.45 ± 98.05
Peak Torso Velocity (AC), deg/s	65.79 ± 65.27
Peak Torso Velocity (AA), deg/s	408.09 ± 39.01
Peak Shoulder Velocity (AA), deg/s	1014.26 ± 472.81
Peak Elbow Velocity (AA), deg/s	184.47 ± 170.61

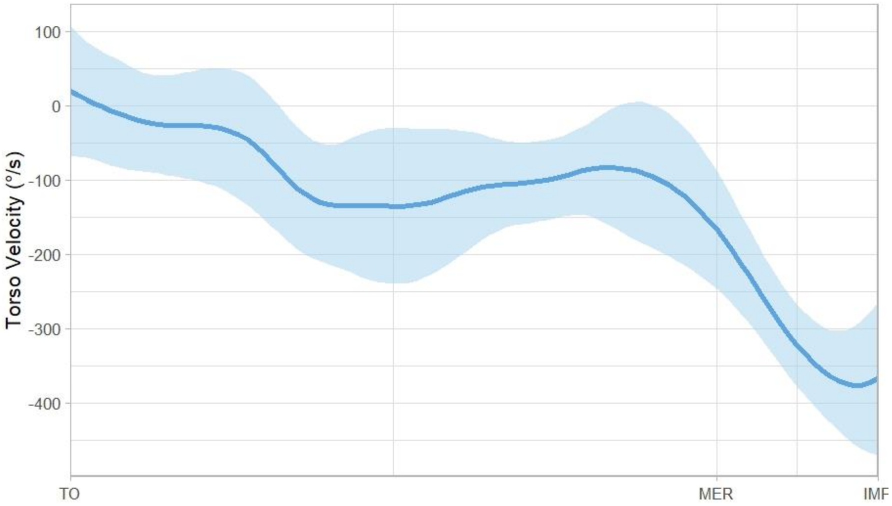

Figure 4. Time series plot (N = 8) for torso velocity (deg/s) throughout the arm cocking (takeoff to MER) and arm acceleration phases (MER to impact). TO – takeoff, MER – maximum external rotation of the shoulder, IMP – impact.

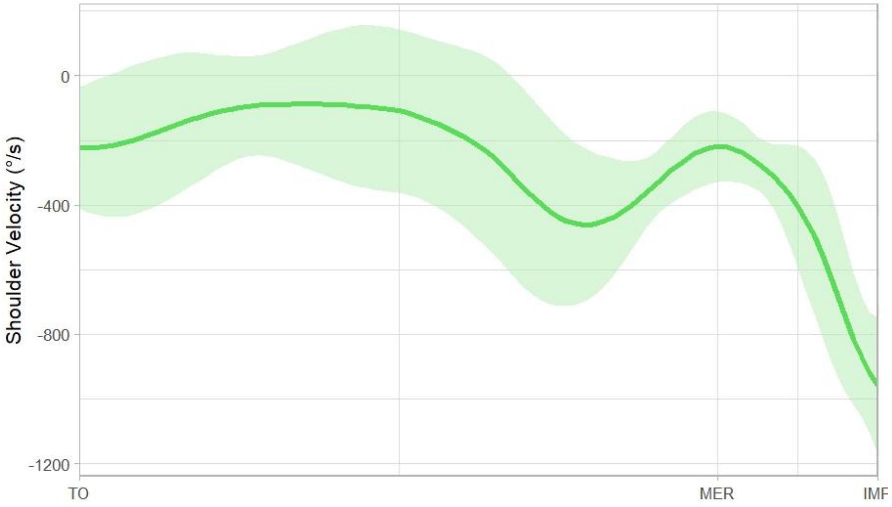

Figure 5. Time series plot (N = 8) for shoulder velocity (deg/s) throughout the arm cocking (takeoff to MER) and arm acceleration phases (MER to impact). TO – takeoff, MER – maximum external rotation of the shoulder, IMP – impact.

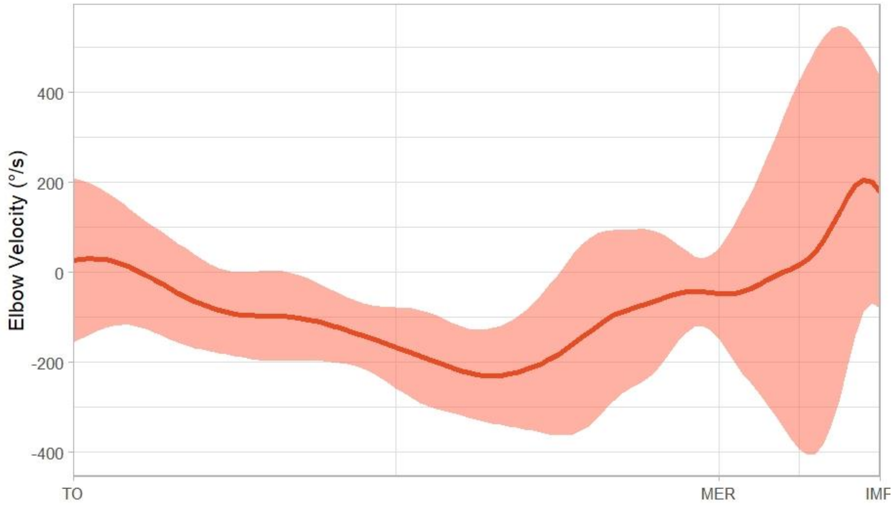

Figure 6. Time series plot (N = 8) for elbow velocity (deg/s) throughout the arm cocking (takeoff to MER) and arm acceleration phases (MER to impact). TO – takeoff, MER – maximum external rotation of the shoulder, IMP – impact.

The multiple stepwise regression analysis indicated that peak torso velocity in the arm cocking phase and peak shoulder and peak elbow velocities in the arm acceleration phase should be included as part of the model that best predicts the ball speed. The ball speed regression model with unadjusted $R^2 = 0.761$ and $p = .098$ was achieved and the equation was ball speed = 16.067 - 0.012*Peak Torso Velocity (AC) – 0.001*Peak Shoulder Velocity (AA) + 0.004*Peak Elbow Velocity (AA). Although the multiple stepwise regression was not statistically significant ($p = .098$), the standard error of estimation of ball speed by the model was 0.727 m/s with the peak torso velocity during the arm cocking phase as the most influential predictor (beta = -.012, $p = .047$).

Table 4

Variables Included in the Ball Speed Multiple Stepwise Regression Analysis. Multiple R^2 *=* *0.761, adjusted* R^2 *= 0.582, F-statistic = 4.254 on 3 and 4 DF, p = .098.*

All Participants (N = 8)	B	β	p
Intercept	16.067		
Peak Torso Velocity (AC)		-0.012	0.047
Peak Shoulder Velocity (AA)		-0.001	0.144
Peak Elbow Velocity (AA)		0.004	0.146

Discussion

Although playing volleyball at a highly competitive level requires proficiency in various skills, attacking is certainly the single most important skill that affects the successfulness of matches (Palao, Santos, & Ureña, 2004). Elite volleyball players must be able to produce high ball speeds during attacking, regardless of their type or approach. In baseball pitching, proximal-to-distal transfer of segmental angular velocity is critical for maximizing ball velocity and reducing the risk of injury of the throwing arm (Scarborough et al., 2018). In the present study, we attempted to discover whether COM approach speed, maximum velocity of pelvis and torso in the arm cocking phase, and maximum velocity of the torso, shoulder IR, and elbow extension during the arm acceleration phase can predict the ball speed in slide attacks.

This study's findings did not fully support the hypothesis that a combination of different variables, including COM approach speed, maximum velocity of pelvis and torso in the arm cocking phase, and maximum velocity of torso, shoulder, and elbow during the arm acceleration phase, would reliably predict the ball speed in slide attacks. Even though the predictive model explained roughly more than half of the variance in ball speed, it was not statistically significant due to the small sample size (N = 8). The model did not include the COM approach speed, peak pelvis velocity in the arm cocking phase, or peak torso velocity in the arm acceleration phase as relevant factors in predicting the ball speed.

Jump height and ball velocity have been defined as the two main performance determinants for the success of spikes in volleyball (Forthomme et al., 2005; Fuchs et al., 2021). When it comes to the jump height, research highlighted the importance of approach speeds, among other relevant factors, in defining the optimal jump mechanics (Bobbert & Schenau, 1988; Wagner et al., 2009). Furthermore, systematic reviews have found strong indications that the spike jump height depends on the velocity of the center of mass (Oliveira et al., 2020). With this existing knowledge regarding the importance of the approach speeds and jump heights in spike performance, it was hypothesized that the COM approach speed would be a relevant predictor of the ball speed in slide attacks. However, the regression model did not include it as a part of the equation.

Maximal angular velocities of the upper extremity during certain phases of the slide attack indicated a role in ball speed, as found in previous studies (Fuchs et al., 2019; Wagner et al., 2012). Aguinaldo and Escamilla (2019) found the trunk rotational torque to be the primary source of power production for ball velocity in baseball pitching, due to the trunk’s large segmental mass. Wagner et al. (2012) highlighted the relevance of the torso momentum and shoulder IR velocity in regular spikes of male volleyball players. Similarly, and in agreement with previous research, the trunk and shoulder motion were the key variables in predicting the ball speed in slide attacks as well. Neither the peak torso velocity in the arm cocking phase nor the peak shoulder IR velocity in the arm acceleration phase were statistically significant, but this can be attributed to the small sample size of the current study.

When it comes to the elbow extension angular velocity, previous studies highlighted its importance in predicting the ball speed of regular spikes in male volleyball players (Wagner et al., 2012). Fuchs et al. reported similar findings for the elbow extension in a basic female volleyball spike (2019). Although not statistically significant, peak elbow extension velocity in the arm cocking phase of slide attacks tended to correlate with the ball speed, which aligned with the findings from previous studies.

Proximal-to-distal transfer of segmental angular velocity characterizes efficient baseball pitching biomechanics (Scarborough et al., 2018). As one segment of the body reaches its peak velocity, it will initiate a rotation of another segment proximal to it and allow the flow of mechanical energy through the kinetic chain (Aguinaldo & Escamilla, 2019). In this study, as seen in Figures 4-6, the torso reached its peak rotational velocity first at 70% of the takeoff to impact phase, followed by the shoulder at 80%, and the elbow at 98%. According to this time-series data (Figures 4-6), it can be concluded that female volleyball players display the typical proximal to distal behavior during slide attacks, as found in regular volleyball attacks and baseball pitching (Marshall & Elliott, 2000; Scarborough et al., 2018). Interestingly, some researchers have found that the maximal elbow extension angular velocity of the hitting arm sometimes occurs before the maximal shoulder IR angular velocity (Serrien, Goossens, & Baeyens, 2018; Wagner et al., 2012). It is believed that this premature elbow extension represents a defense mechanism in order to reduce the moment arm for the shoulder IR. This way, the elbow extension angular velocity reduces and prevents overextension of the elbow, thus, reducing the risk of possible muscle or joint injuries (Wagner et al., 2012). However, this behavior was not displayed in this study’s sample. By relying on previously discussed determinants for predicting the ball speed in pitching, which indicate that the mechanical power of the trunk and shoulder are the key variables in predicting the ball speed, further studies would benefit from an energy flow analysis of slide attacks (Aguinaldo & Escamilla, 2019).

Limitations

This study adds valuable baseline information to the limited research on slide attacks, but it is not without limitations. The major limitation of this study is the sample size, which consisted of only 8 participants. The study was conducted during the COVID-19 pandemic and, although all precautions were taken, the ability to recruit participants was limited. Furthermore, the slide attack is a typical attack performed by middle blockers, so players who serve as middle blockers are naturally more comfortable with performing slide attacks. However, even though all participants of this study were actively participating in volleyball and served as pin-hitters, they were not all middle blockers. In addition, the single group study design prevented the comparison of ball speed predictors in slide attacks between collegiate and other competitive levels of volleyball. It is possible that the biomechanical characteristics and differences in techniques observed among players of different levels exist. Future studies should prioritize recruiting a larger sample size of middle blockers so that the consistency of slide attack techniques and proficiency is achieved and the probability of observing statistical significance, where present, is maximized.

Another limitation of this study is the exclusion of the lower body segments in the analysis model, regardless of their reported contribution to the transfer of energy up the kinetic chain and their effects on the spike jump mechanics in volleyball (Aguinaldo & Escamilla, 2019; Wagner et al., 2009). This study attempted to take an innovative approach to volleyball biomechanics research and perform the data collection in the natural environment where volleyball players compete. However, it also limited the ability to investigate ground reaction forces and lower extremity kinetics, which are important factors in optimal jump and jump height mechanics and, thus, determine the success of spikes in volleyball (Forthomme et al., 2005; Wagner et al., 2009).

Current research suggests that improper pitching mechanics and elbow valgus torque lead to various injuries in pitchers, from ulnar collateral ligament, flexor-pronator mass, and ulnar nerve injuries in professional players, to other lateral side injuries in younger players (Aguinaldo & Escamilla, 2019). With shoulder pain and discomfort accounting for 8-20% of all volleyball-related injuries, and the high number of repetitions and power required for a successful volleyball swing that increase the risk of a potential shoulder injury, future studies should look into the effects of shoulder and elbow forces and torques on slide attack ball speed and injury risk (Reeser et al., 2010).

Conclusion

In conclusion, this study represents the first known study to investigate the biomechanical predictors of ball speed in slide attacks in collegiate female volleyball players. The findings indicate that peak torso velocity in the arm cocking phase and peak shoulder and peak elbow velocities in the arm acceleration phase are important contributors to the ball speed in slide attacks. Still, the most influential contributor to the ball speed is peak torso velocity during the arm cocking phase. Therefore, when it comes to technique-related player improvements, coaches should emphasize the importance of achieving a large trunk rotation and doing so quickly throughout the arm cocking phase. This could be a possible mechanism for minimizing hitting-related shoulder injuries. However, additional research is needed to investigate the contributions of the lower extremity kinetics and kinematics and shoulder and elbow forces and torques to ball speeds in slide attacks, as well as define how improvements in technique impact injury risk.

Finally, the effects of fatigue on a larger sample size as well as an energy flow analysis should be addressed in future studies as well.

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