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Rotational Angles and Velocities During Down the Line and Diagonal Across Court Volleyball Spikes

Justin R. Brown (Corresponding author)
Department of Exercise and Sport Science, University of Utah
250 S. 1850 E., HPER North, RM 241, SLC, UT
Tel: 1-801-585-7325 E-mail: brown.justin@utah.edu

Bader J. Alsarraf
Department of Physical Education, College of Basic Education in Kuwait
Adailiya, Kuwait
Tel: 965-99591661

Mike Waller
Department of Exercise Science and Health, University of Saint Francis
2701 Spring St, Fort Wayne, IN, 46808
Tel: 1-260-399-7999 E-mail: MWaller@sf.edu

Patricia Eisenman
Department of Exercise and Sport Science, University of Utah
250 S. 1850 E., HPER North, RM 241, SLC, UT
Tel: 1-801-581-7929 E-mail: patricia.eisenman@hsc.utah.edu

Charlie A. Hicks-Little
Department of Exercise and Sport Science, University of Utah
250 S. 1850 E., HPER North, RM 241, SLC, UT
Tel: 1-801-581-4897 E-mail: Charlie.hickslittle@hsc.utah.edu

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Abstract

The volleyball spike is an explosive movement that is frequently used to end a rally and earn a point. High velocity spikes are an important skill for a successful volleyball offense. Although the influence of vertical jump height and arm velocity on spiked ball velocity (SBV) have been investigated, little is known about the relationship of shoulder and hip angular kinematics with SBV. Other sport skills, like the baseball pitch share similar movement patterns and suggest trunk rotation is important for such movements. The purpose of this study was to examine the relationship of both shoulder and hip angular kinematics with ball velocity during the volleyball spike. Methods: Fourteen Division I collegiate female volleyball players executed down the line (DL) and diagonally across-court (DAC) spikes in a laboratory setting to measure shoulder and hip angular kinematics and velocities. Each spike was analyzed using a 10 Camera Raptor-E Digital Real Time Camera System. Results: DL SBV was significantly greater than for DAC, respectively (17.54±2.35 vs. 15.97±2.36 m/s, $p<0.05$). The Shoulder Hip Separation Angle (S-H_{SA}), Shoulder Angular Velocity (S_{AV}), and Hip Angular Velocity (H_{AV}) were all significantly correlated with DAC SBV. S-H_{SA} was the most significant predictor of DAC SBV as determined by regression analysis. Conclusions: This study provides support for a relationship between a greater S-H_{SA} and SBV. Future research should continue to 1) examine the influence of core training exercise and rotational skill drills on SBV and 2) examine trunk angular velocities during various types of spikes during play.

Keywords: performance, volleyball, attack, rotation

1. Introduction

The volleyball spike is one of the most explosive movements in volleyball and is frequently used to end a rally and earn a point. The ability to execute a high velocity volleyball spike is an important skill for a successful volleyball offense because it decreases the ability of the defense to keep the ball in play (Ferris, Signorile, and Caruso, 1995; Forthomme, Croiser, Ciccarone, Crielaard, Clores, and Cloes, 2005). Reported spiked ball velocities (SBV) range from 25 to 28 m/s for male players (Forthomme et al., 2005; Coleman, Benham, and Northcott, 1993) and 13.5 to 18.1 m/s for female players (Ferris et al., 1995; Newell and Lauder, 2005; Reeser, Fleisig, Bolt, and Ruan, 2010). While spike jump height is an important determinant of a high SBV (Forthomme et al. 2005; Hussain, 2012), trunk and shoulder movements occurring during the hitting action of the spike also contribute to SBV (Ferris et al., 1995; Newell, 2005).

Coleman et al. (1993) was the first to use a three-dimensional cinematographic analysis to examine the role of trunk rotation on SBV with a study on elite male volleyball players. Spikes were filmed and analyzed from games at an international competition. Trunk rotation (about the y-axis) was evaluated by measuring the shoulder hip separation angle (S-H_{SA}) (degrees) (Figure 1), shoulder angular velocity (S_{AV}) and hip angular velocity (H_{AV}) (rad s^{-1}). The S-H_{SA} was defined as the angle between the horizontal plane projections of the lines joining the two glenohumeral and the two hip joints. All spikers were right handed so the mean negative peak S-H_{SA} (-46.6°±2.9) indicated rightward rotation of the torso during the initial portion of the backswing or cocking phase of the spike. Neither the peak S-H_{SA} nor the associated peak shoulder-hip angular velocity (13.5 rad s^{-1}±1.66) was significantly related to SBV. Coleman et al. (1993) hypothesized this lack of significance may be a reflection of directionality of the spikes filmed in his study. Since the film for analysis was taken during game play the direction of the spikes was not systematically controlled by the researchers. Some of the spikes were down the line and some were across-court spikes. Coleman et al. (1993) reasoned that most of the spikes analyzed were across-court spikes which may not involve the same amount of rotation as a down the line spike, leading him to conclude that it was "not surprising that no correlation was found between the amount of trunk rotation and ball speed."

More recently, Newell and Lauder (2005) investigated upper body kinematics and SBV for elite and club female players. During spike-performance tests, which were limited to across-court, elite volleyball players exhibited a 34% higher ball velocity compared to club volleyball players (mean 18.1±1·1 m.sec^{-1} and 13.5±0·9 m.sec^{-1} respectively). The higher SBV for the elite players was associated with significantly more forward rotation of the trunk (p=.05), but neither peak S-H_{SA}, S_{AV}, or H_{AV} were reported. Similarly, in 2012, Wagner, Pfusterschmied, Tilp, Landlinger, von Duvillard, et al. (2012) examined shoulder and hip rotation angles and velocities during the spike in elite male players, but neither peak S-H_{SA} or peak should-hip angular velocity were reported and the relationship of the spike kinematic variables to SBV was not considered.

Although several researchers have examined kinematics during a volleyball spike, there is a paucity of literature regarding the influence of peak S-H_{SA} as well as S_{AV} and H_{AV} on SBV, especially for female collegiate volleyball players. Furthermore, it is unclear if spiking direction influences the contribution of the S-H_{SA}, S_{AV} and H_{AV} to SBV. The purpose of this study was to quantify peak S-H_{SA}, S_{AV}, H_{AV}, and SBV for both DL and DAC spikes in order to determine the relationships between these variables and SBV. Based on the comments of Coleman et al. (1993), we hypothesized that DL spikes will have significantly greater S-H_{SA}, S_{AV}, and H_{AV} resulting in greater SBV than DAC spikes.

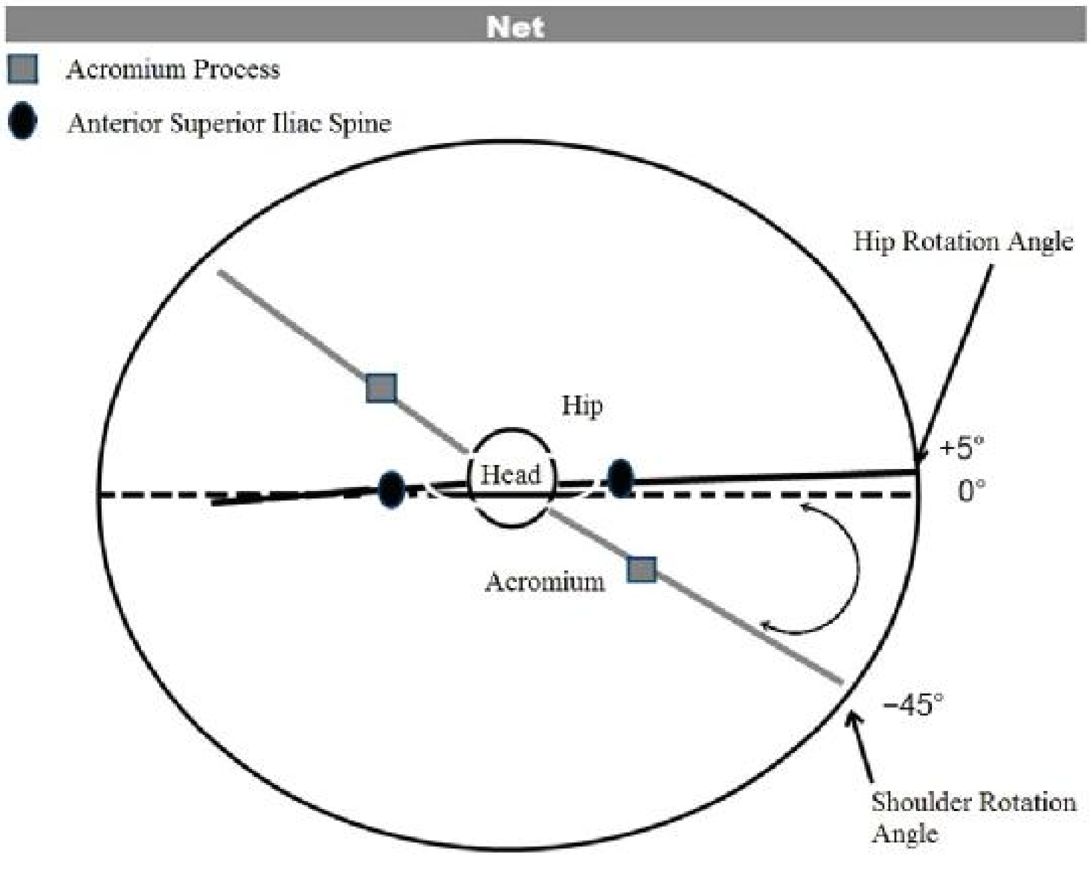

Figure 1: Illustration of shoulder and hip rotation angles. Note the dashed line represents the neutral position and the solid grey line represents the positioning of the upper torso at the conclusion of the back swing. The solid black line represents the positioning of the hips as they begin forward motion prior to forward motion of the upper torso. The hip is +5° and the shoulder is -45°, the difference between the two is S-H_{SA}.

2. Method

2.1 Participant

Fourteen National Collegiate Athletic Association Division I female volleyball players between the ages of 18 and 30 years and 3.2 ± 1.4 years of playing experience participated in this study (Table 1). Six players were outside hitters, 3 were middle blockers, 3 were setters, and 2 were liberos; however, prior to their collegiate careers, all of the players had experience as spikers. Therefore a range of spiking ability and presumably SBV was monitored. None of the players had either acute or chronic injuries that interfered with the ability to execute a volleyball spike as determined by a health history questionnaire. Finally, all but one of the players was right handed. Data was collected during the volleyball off-season. Players were asked to arrive at the laboratory in a rested and normally hydrated state having not eaten during the previous three hours. All participants signed written informed consent prior to testing. Approval for the study was given by the Intuitional Review Board from the University of Utah.

Table 1. Descriptive Data for the Sample of 14 Female Collegiate Volleyball Athletes.

Variable	*M* ± *SD*
Age (yrs)	20.9±2.8
Height (cm)	181.6±7.7
Body Mass (kg)	72.9.3±12.5
Body Mass Index (kg/m²)	22.0±3.0
Body Fat % (ADP)	22.0±6.3
Fat Free Mass (kg)	56.3±7.0
Fat Mass (kg)	16.5±7.5

2.2 Anthropometrics

During the off-season and prior to pre-season fitness testing sessions, athletes were measured for anthropometric data with athletes wearing lycra shorts, sports bras, and a swim cap. Height was measured to the nearest 0.1 cm using a stadiometer, body mass was measured within 0.01 kg on a calibrated electric scale, and body composition was assessed using Air Displacement Plethysmography (Bod Pod, Life Measurement Inc., Concord, CA). The Siri equation was used to calculate percent body fat. Equipment was calibrated prior to testing according to manufacturer's recommendations (Dempster and Aitkens, 1995; Fields, Goran, and McCrory, 2002).

2.3 Angular Kinematics

Three-dimensional motion capture analysis was used to study the kinematics of the volleyball spike. To facilitate analyzing shoulder and hip motions, each participant wore a sport pro bra, fitted shorts, and a total of 21 reflective markers (19 mm). Reflective markers were placed on the following anatomical landmarks: the right and left acromion process; the right and left inferior angle of the scapula; the right and left medial border of the scapula; the 7th cervical vertebra; the sternal notch, the xiphoid process, the right lateral epicondyle of the humerus; the right medial epicondyle of the humerus; upper medial shaft of the right of the humerus; right medial forearm; right wrist lateral styloid process and right wrist medial styloid process; the right hand 3rd MCP joint; the right and left anterior superior iliac spine (ASIS); the right and left posterior superior iliac spine (PSIS); and the V sacral. The reflective markers were placed on the participants prior to their warm-up.

The markers' movements during each spike were analyzed with a 10 Camera Raptor-E Digital Real Time Camera System (Motion Analysis Corporation, Santa Rosa, CA). Kinematic data were collected at a sampling rate of 120 Hz and raw data were first processed to eliminate any noise artifact. All kinematic coordinate data were low pass filtered at 6 Hz using a 2nd-order zero lag Butterworth digital filter and were then processed using motion analysis software. The motion capture analyses were completed in the Sports Medicine Research Laboratory located at the University of Utah. The three-dimensional motion capture analysis measured S_{AV} and H_{AV} (degrees/second) during the hitting phase of each volleyball spike, as well as S-H_{SA} (degrees) at the conclusion of the backswing or cocking phase of the spike (Oka, Okamoto, and Kumanamoto, 1976). The S-H_{SA} was defined as the angle between the horizontal plane projections of the lines joining the two acromion processes and the two anterior superior iliac spine processes (Coleman et al., 1993). The reader is referred to Coleman et al., 1993 for a complete description of the volleyball spike.

The motion capture analysis was also used to measure SBV in meters per second. An official size and weight Baden® Lexum™ Comp VX450 volleyball was used for the volleyball spike tests. Three reflective markers were placed on the front surface of the ball. To allow athletes to place the ball at an optimal height, a fixed ball position (Tilp, Wagner, and Müller, 2008; Wagner, Tilp, von Duvillard, and Müller, 2009) was used by employing a SPIKE IT® (JumpUSA, Sunnyvale, CA). In addition the SPIKE IT® was used to decrease variability between sets that may occur using a setter. Prior to testing, the participants were allowed to adjust the height of the ball in the SPIKE IT® based on their preference; this height was measured and maintained for all spikes. The SPIKE IT® was placed near the center of a regulation height, simulated net on the same side from which the player performed the volleyball spikes. Additionally, in order to catch the spiked balls and protect the motion capture analysis cameras, netting was strategically positioned. The DL and DAC targets were placed 3 meters behind the capture netting.

Participants were instructed to engage in a 5 minute self-selected warm-up before performing the volleyball spikes. Following warm-up, the players were instructed to perform a 3-4 step approach and spike the volleyball with maximum force and velocity using their dominant arm. Participants executed 10 DL and 10 DAC spikes with 30 seconds recovery between spikes. Participants were given 5 minutes rest between DL and DAC spikes and the order of spiking direction was randomized. The directionality for the DL and DAC spikes for right and left-handed participants are illustrated in Figures 2 and 3. A spike was repeated if the target was not hit. The first 3 spikes from each direction were considered to be practice trials. The remaining 7 spikes were retained to calculate mean and perform data analysis.

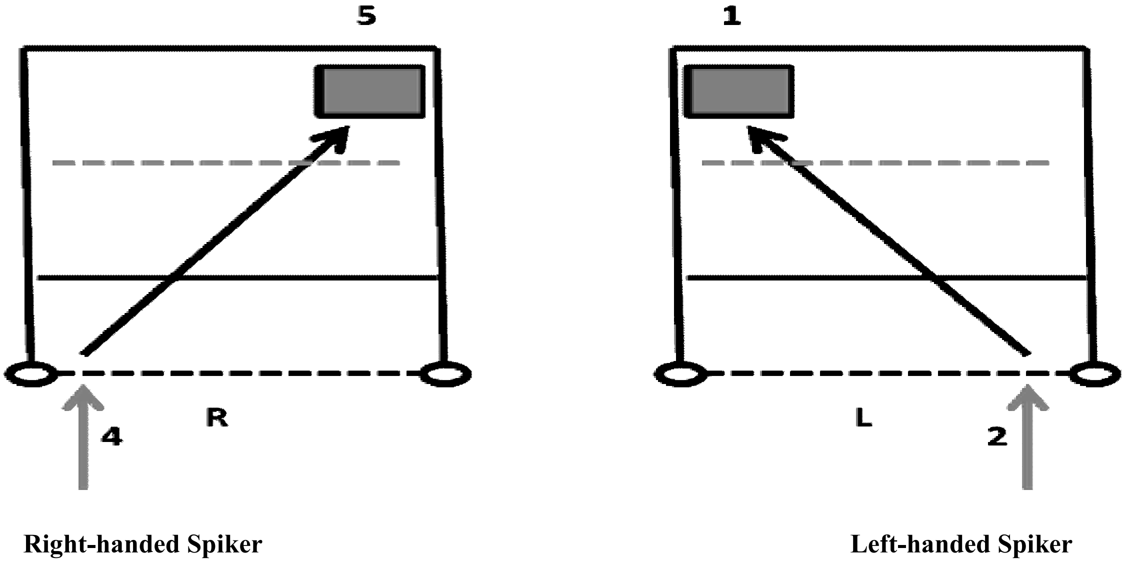

Figure 2: Diagonally across-court spikes for right and left handed spikers. Note: grey boxes represent targets players were instructed to hit during each volleyball spike.

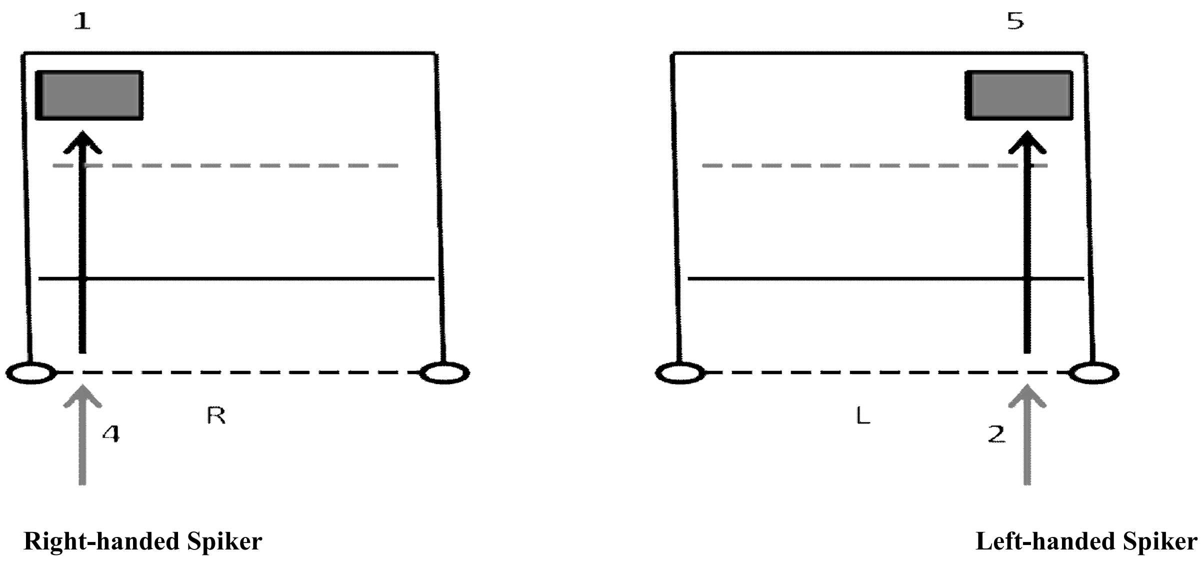

Figure 3. Down-the-line spikes for right and left handed spikers. Note: grey boxes represent targets players were instructed to hit during each volleyball spike.

2.4 Research Design

This study investigated the kinematic characteristics of Division I female collegiate volleyball players executing volleyball spikes. A cross-sectional, descriptive design was used to quantify the kinematic characteristics for DL and DAC volleyball spikes in a laboratory setting. The order of DL and DAC spikes were randomized and three-dimensional motion capture analysis was used to quantify SBV, S-H_{SA}, S_{AV}, and H_{AV} for the two spiking actions.

2.5 Data Analysis

Data are presented as mean and SD. Paired t-tests were used to examine the significance of the spiking direction (DL vs. DAC) differences for SBV, $S\text{-}H_{SA}$, S_{AV}, and H_{AV}. Pearson Product Moment Correlation Coefficient (r) analyses were used to determine if SBV was related to $S\text{-}H_{SA}$, S_{AV}, and H_{AV} for both DL and DAC spikes. The stability of the 7 SBV trials for both DL and DAC spikes were determined by using a two-way factor mixed (participants random and trials fixed) repeated measures factorial ANOVA. A multiple regression analysis was used to determine which angular variable best predicted SBV. The analyses were performed using PASW Statistical software (Version 18.0, Chicago, IL, USA).

3. Results

The ANOVA results indicated that the mean values for the 7 SBV trials for both DL and DAC were not statistically different from one another indicating stability among spikes, respectively (F=1.06, p=.394; F=.426, p=.859). Descriptive statistics and level of significance for the comparison of SBV, $S\text{-}H_{SA}$, S_{AV}, and H_{AV} between the DL and DAC spikes are presented in Table 2. Statistical significance was observed for SBV between DL and DAC spikes. Statistically significant differences were also seen for $S\text{-}H_{SA}$ between DL and DAC spikes (-9.16±-5.32° vs. -12.65±-5.36°).

Table 2. Means, Standard Deviations, Ranges, and p-Values for Spiked Ball Velocity, Peak Shoulder Hip Separation Angles, Peak Shoulder Rotational Velocity, and Peak Hip Rotational Velocity During Volleyball Spikes for Down-the-Line (DL) and Diagonally Across-Court (DAC).

Variable	DL *M ± SD* Range	DAC *M ± SD* Range	*p*-value sig.
SBV (m/s)	17.54±2.35	15.97±2.36	**.039**
	13.59-21.83	11.95-20.47	
$S\text{-}H_{SA}$	-9.16±-5.32	-12.65±-5.36	**.043**
	-2.63 to -21.28	-3.00 to -20.43	
S_{AV}	363.57±67.35	362.48±79.87	.474
	251.16-538.64	209.17-487.13	
H_{AV}	194.01±64.41	180.33±64.07	.129
	99.63-304.84	74.84-276.14	

Note: Gender: female, *n*=14. SBV=spiked ball velocity; $S\text{-}H_{SA}$=Shoulder Hip Separation Angle; S_{AV}=Shoulder Angular Velocity; H_{AV}=Hip Angular Velocity; m/s=meters per second.

The Pearson Product Moment Correlation Coefficients and level of significance for the comparisons between SBV and the other variables are presented in Table 3. Moderate positive correlation coefficients were observed between SBV and $S\text{-}H_{SA}$ (r=0.56, p=0.019) at the top of the backswing phase, S_{AV} (r=0.66, p=0.005) during the forward swing phase, and H_{AV} (r=0.47, p=0.044) during the forward swing phase for the DAC spikes. Additionally, a non-significant low to moderate positive correlation was observed between SBV and $S\text{-}H_{SA}$ (r=0.31, p=0.142) at the top of the backswing phase for the DL spikes. A multiple regression analysis predicting SBV from the rotational variables for DAC spikes resulted in a statistically significant multiple R^2 value as seen in Table 4. $S\text{-}H_{SA}$ was the most important predictor of SBV. The R^2 value for the multiple regression analysis for DL spike was not statistically significant.

Table 3. Pearson Product Moment Correlation Coefficients (r) Between Spiked Ball Velocity and the angular kinematic variables Assessed for Down-the-Line (DL) and Diagonally Across-Court (DAC) Spikes.

Variable	*DL*		*DAC*	
	r	p value	r	p value
$S\text{-}H_{SA}$	0.31	0.142	0.56	**0.019**
S_{AV}	0.09	0.387	0.66	**0.005**
H_{AV}	0.06	0.421	0.47	**0.044**

Note: Significant relationships are shown in bold font. Gender: female, *n* = 14. $S\text{-}H_{SA}$=Shoulder Hip Separation Angle; S_{AV}=Shoulder Angular Velocity; H_{AV}=Hip Angular Velocity; DL=Down the Line; DAC=Diagonally-across Court.

Table 4. Regression Analysis Summary for Female Collegiate Volleyball Athletes Predicting SBV for DAC Spikes.

Variable	B	SEB	Beta
Constant	8.480	2.68	
S-H_{SA}	.196	.112	.45
S_{AV}	.007	.009	.25
H_{AV}	.013	.010	.35

Note: R^2=.58 (*N*=14, *p*<.05). S-H_{SA}=Shoulder Hip Separation Angle; S_{AV}=Shoulder Angular Velocity; H_{AV}=Hip Angular Velocity.

Table 5. Comparison of Means (SD) for Ball Speed for Males and Females During Volleyball Spike Performance.

Sex	Author	Competative Level	N	SBV (m/s)
Male	Coleman et al., 1993	Senior international	10	27.0±0.9
Male	Forthomme et al., 2005	Professional – D1	11	28.02±1.66
Male	Forthomme et al., 2005	Professional – D2	8	25.11±2.30
Male (I)	Mitchinson et al., 2013	International	24	19.4±2.4
Male (NI)	Mitchinson et al., 2013	International	24	19.0±2.0
Female	Ferris et al., 1995	NCAA – D1	13	18.1±1.77
Female	Newell & Lauder., 2005	Elite	5	18.1±1.0
Female	Newell & Lauder., 2005	Club	3	13.5±0.9
Female	Present study (DL)	NCAA – D1	14	17.54±2.35
Female	Present study (DAC)	NCAA – D1	14	15.97±2.36
Female	Reeser et al., 2010 (SA)	NCAA – D1	14	15.5±2.0
Female	Reeser et al., 2010 (CB)	NCAA – D1	14	15.7±1.7

Note: D1 = first division Belgium League, D2 = Second Division Belgium League, NCAA = National Collegiate Athletic Association, DL = Volleyball spike down the line, DAC = Volleyball spike diagonally across court, I = Injured, NI = Non-injured, SA = Strait Ahead, CB = Cross Body.

4. Discussion

This is the first study to contrast SBV for both DL and DAC spikes executed by female collegiate athletes. The purpose was to examine relationships between SBV and S-H_{SA}. While references have been made to the role of trunk rotation on SBV in female athletes, this is the first study to use S-H_{SA} to quantify trunk rotation for female athletes. Coleman et al. (1993), monitoring in-competition values for international level male athletes, reported a mean S-H_{SA} of -41.6^o (S.E.+-2.9^o); a value that is much larger than either the DL or DAC S-H_{SA} values reported in the current study. More recently, other researchers (Mitchinson, Campbell, Oldmeadow, Gibson, and Hopper, 2013) have used kinematics during the spike to study shoulder injury variables. Trunk rotation to the right was -59^o for uninjured and -62.6^o for injured athletes during the backswing. Both values are substantially larger than the S-H_{SA} values reported in the current study.

Since no other researchers have reported S-H_{SA} values for female spikers it is impossible to make direct comparisons. However, Newell and Lauder (2005) in their analysis of elite and club level female athletes did report that the club level athletes had less forward rotation of the trunk than the elite athletes who had higher velocity spikes, suggesting a smaller range of motion associated with a smaller S-H_{SA}. Also, a visual comparison of the body rotation kinematic figures depicting the females by Newell and Lauder (2005) with the figures of males from Coleman et al. (1993) shows greater trunk rotation by the male spikers, which would be associated with a larger S-H_{SA} and higher velocity spikes.

Differences in testing conditions (laboratory vs. competition settings) and the motion capture analysis equipment used might have contributed to the differences in the above S-H_{SA} values; however, it is more likely that some combination of experience and trunk muscular strength differences were responsible. Both the females in the current study and the males in the Coleman (1993) study used various combinations of the 'backswing' and 'elevation' spiking styles (Oka et al., 1976), but spiking style was not systematically analyzed in the current study so differences in S-H_{SA} can't be solely attributed to different spiking styles. However, it is likely that training experienced by the elite male athletes in the Coleman et al. (1993) may have contributed to the male athlete's ability to achieve larger S-H_{SA} values than less experienced female athletes in the current study.

It is also possible that the documented differences in muscular strength between male and female athletes contributed to the difference in S-H_{SA} between previous studies (Coleman et al., 1993, Mitchinson et al., 2013) and the current study.

Greater leg strength and power in elite athletes would contribute to higher spike jumps (Wagner et al., 2009), allowing for more time in the air to achieve more S-H_{SA}. Greater strength of the upper trunk musculature of elite males compared to the collegiate females in the current study, might allow a greater S-H_{SA} in the cocking phase of the spike.

The SBV values observed in the current study compare favorably to other values for female athletes and are slower that those reported for male athletes (see Table 5) This study also demonstrated SBV to be significantly faster for DL spikes compared to DAC spikes (17.54±2.35 vs. 15.97±2.36 m/s). Reeser et al. (2010) reported no difference in SBV for cross-body and DL spikes (15.7±1.7 vs. 15.5±2.0 m/s) for female collegiate volleyball players. Similarly, Mitchinson et al. (2013) did not observe a difference in SBV for DL and DAC spikes. The difference in SBV between the DL and DAC spikes in the current study may be partially explained due to playing status (elite and club vs. collegiate) for the studies compared. Differences in study designs may also explain differences between studies. For example, Reeser et al. (2010) had players spike a ball that was set by a single investigator whereas we had players spike the ball from a fixed position using a SPIKE IT®. While Mitchenson et al. (2013) also used a ball in a fixed position (Tilp et al. 2008), the fixed position was achieved by hanging the ball from the ceiling with Velcro strips attached to the ball so that the ball would break away upon hand contact. It is possible that positioning of the SPIKE IT® caused a systematic difference in resistance between the DL and DAC spikes. Such a systematic difference could have contributed to the significantly greater DL SBV observed compared to the DAC SBV.

Although both Mitchinson et al. (2013) and Reeser et al. (2010) used laboratory settings, the space available in their laboratories was greater than in our laboratory. Therefore to protect the 10 motion capture cameras we used netting to trap the spiked balls. The netting on the sides of the court may have limited approaches for the DAC spikes. Since spike jump height is an important factor for SBV (Hsieh and Christiansen, 2010), if the environmental conditions limited the approaches for the DAC spikes, this may have limited the spike jump heights leading to a slower SBV for the DAC spikes in the current study. In addition, cameras were in a direct line with the DAC target areas so it is also possible that even though a larger S-H_{SA} was achieved with the DAC spike, some athletes may have hesitated to hit the ball with maximal force due to camera positioning in the laboratory. In other words, some athletes may have sacrificed velocity for control so that they would not spike the ball into the cameras on their DAC spikes, contributing to the slower mean DAC SBV observed in the current study.

The statistically significant relationship observed between SBV and S-H_{SA} for the DAC spikes ($r=0.56$; $p=0.019$) again contrasted with the results of Coleman et al. (1993) since they did not find a significant relationship. Although Coleman et al. did not distinguish between DL and DAC spikes, they reported that most of the spikes analyzed were DAC. Coleman et al. (1993) analyzed spikes during top-level competition, so variability in positioning of the sets as well as other factors might have contributed to the lack of correlation between SBV and S-H_{SA}. Furthermore, the ten participants in the Coleman et al. (1993) study represented a homogenous group of highly skilled international competitors, reducing the likelihood of sufficient variability in performance to yield the distribution necessary for a significant correlation. Conversely, there was much more variability in the spiking skill of the participants in the current study. Inclusion of a wider skill range probably contributed to the correlation coefficients observed in the current study.

In this study a significant correlation was observed between SBV and S-H_{SA} for the DAC spikes; however, the relationship between SBV and S-H_{SA} for the DL spikes was small ($r=0.31$) and not statistically significant. Perhaps, with DL spikes some of the less skilled athletes used trunk hyperextension rather than trunk forward rotation to generate arm velocity to transfer to the ball. Newell and Lauder (2005) noted that less skilled club players used more trunk hyperextension and less forward rotation than the elite players in their study.

The correlation coefficients observed between S-H_{SA} and SBV, particularly for the DAC spikes, provide some support for the importance of S-H_{SA} at the top of the backswing as a contributor to SBV and agrees with work published by sport scientists (Stodden, Fleisig, McLean, Lyman, and Andrews, 2001; Szymanski DJ, McIntyre, Symanski JM, Bradford, Schade, et al., 2007; Myers, Lephart, Tsai, Sell, Smoliga, et al., 2008) studying other sport skills. Myers et al. (2008), when examining the golf swing, reported that increased S-H_{SA} at the top of the backswing is a more important contributor to ball velocity than are the magnitudes of either the shoulder or hip angular velocities. Such an observation is consistent with kinetic link theory (Coleman et al., 1993; Stodden et al., 2001).

According to kinetic link theory, in order to produce maximum SBV, the force produced by hip rotation must be correctly timed with the sequential movements involving shoulder rotation and the arm/wrist so that optimal velocity is transferred to the ball (Stodden et al., 2001; Szymanski et al. 2007; Myers et al. 2008; Aguinaldo, Buttermore, and Chambers, 2007). The correlations between SBV and S-H_{SA}, especially for DL spikes, represent some support for kinetic link theory. When a larger S-H_{SA} is achieved, and forward rotation of the shoulder occurs while the hip position is maintained, more momentum will be sequentially transferred from the larger body segments (trunk and shoulders) to the smaller distal segments (arm and wrist) and the ball, resulting in a higher SBV than with a smaller S-H_{SA}.

Limitations of this study include a small sample size (n=14), consiting of females only, a single skill level and narrow age range. Thus, the findings may not apply to all volleyball players. In addition, the use of the SPIKE-IT® to fix the ball position proved to be a limitation because it did not allow for a full-sized volleyball court in the laboratory setting. A play/game situation could change the approach steps, positioning for the spike, and the resistance to the flight of the ball when hit from a set rather than a SPIKE-IT®. Future research should consider the influence of different 'set' positions and types as well as making comparison observations during actual play/games. Longitudinal studies to examine the influence of strategies to develop a larger S-H_{SA} on SBV would also be beneficial.

In summary, the significant correlation between S-H_{SA} and SBV for DAC spikes and the moderate correlation between S-H_{SA} and SBV for DL spikes suggest that increasing S-H_{SA} is a potential strategy for increasing SBV. The study results also suggest that S-H_{SA} should be increased by limiting the amount of hip rotation during the final phase of the backswing.

Although this is a correlational study and no causal relationships can be made, there are associations between the maximum SBV and the magnitude of S-H_{SA} during the spike backswing. Accordingly, the incorporation of core rotational exercises into the strength and conditioning programs for volleyball players specializing as outside hitters may help improve SBV, especially for DAC spikes. In addition, spiking drills that emphasize creating S-H_{SA} during the backswing might help players impart more velocity to the spiked ball. Such drills and exercises might be particularly important for female, non-elite athletes.

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