[Athletic Training]

Upper Limb Biomechanics During the Volleyball Serve and Spike

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Background: The shoulder is the third-most commonly injured body part in volleyball, with the majority of shoulder problems resulting from chronic overuse.

Hypothesis: Significant kinetic differences exist among specific types of volleyball serves and spikes.

Study Design: Controlled laboratory study.

Methods: Fourteen healthy female collegiate volleyball players performed 5 successful trials of 4 skills: 2 directional spikes, an off-speed roll shot, and the float serve. Volunteers who were competent in jump serves (n, 5) performed 5 trials of that skill. A 240-Hz 3-dimensional automatic digitizing system captured each trial. Multivariate analysis of variance and post hoc paired t tests were used to compare kinetic parameters for the shoulder and elbow across all the skills (except the jump serve). A similar statistical analysis was performed for upper extremity kinematics.

Results: Forces, torques, and angular velocities at the shoulder and elbow were lowest for the roll shot and second-lowest for the float serve. No differences were detected between the cross-body and straight-ahead spikes. Although there was an insufficient number of participants to statistically analyze the jump serve, the data for it appear similar to those of the cross-body and straight-ahead spikes. Shoulder abduction at the instant of ball contact was approximately 130° for all skills, which is substantially greater than that previously reported for female athletes performing tennis serves or baseball pitches.

Conclusion: Because shoulder kinetics were greatest during spiking, the volleyball player with symptoms of shoulder overuse may wish to reduce the number of repetitions performed during practice. Limiting the number of jump serves may also reduce the athlete's risk of overuse-related shoulder dysfunction.

Clinical Relevance: Volleyball-specific overhead skills, such as the spike and serve, produce considerable upper extremity force and torque, which may contribute to the risk of shoulder injury.

Keywords: volleyball; shoulder; elbow; kinematics; kinetics; overuse

Shoulder pain and dysfunction account for 8% to 20% of all volleyball-related injuries.[5] Data collected prospectively by the National Collegiate Athletic Association's Injury Surveillance System on injuries occurring in women's collegiate volleyball indicate that shoulder problems rank third overall as a cause of time-loss injury (behind ankle sprains and anterior knee pain), with an injury incidence of 0.65 per 1000 athlete exposures.[1] This injury rate may actually underestimate the true incidence of shoulder problems among female collegiate volleyball players, given that overuse-related pathology often begins insidiously and may not initially result in time lost from training or competition.

However, the consequences of time-loss shoulder injuries are not trivial. Verhagen et al[32] reported that the mean time loss from a volleyball-related shoulder injury is approximately 6.2 weeks—longer than for any other injured body part. Wang and Cochrane[34] reported that, at some point during the 2-year period of their study, approximately 40% of English first-division male volleyball athletes lost time from training or competition because of shoulder problems.

Of the overhead volleyball skills, the spike is perhaps the most explosive. Spikes, or attacks, are typically high-velocity shots (ball speeds can approach 28 m per second).[18] An elite volleyball athlete, practicing between 16 and 20 hours a week,

may perform 40 000 (or more) spikes in a single season.[19] Not surprisingly, players who specialize in the attacking aspect of the game (eg, outside hitters, opposites, and middle blockers) are more likely to develop shoulder pain and dysfunction.[25]

Although the spike is performed to terminate a rally and win the point, the serve initiates every point. Two serving styles predominate: the traditional float serve and the more dynamic jump serve. The float serve remains the most popular serve employed by female collegiate volleyball players. Reeser et al determined that athletes who perform the jump serve are more likely to experience shoulder problems than are those who use the float serve.[25]

Early studies of volleyball biomechanics described the gross motor pattern of the spike.[2,8,21,29] In addition, a few studies focused on upper extremity kinematics during the spike—correlating shoulder and elbow motion with ball velocity,[8] hand velocity,[7] and jump height.[31,33] Two studies also determined the muscle activation patterns involved in spiking and serving.[22,27]

Published data on upper extremity kinetics for volleyball spikes are limited. Rinderu[26] found that the maximal glenohumeral joint reaction force during spiking was greater in male players than in female players. In a small study (n, 6), Plawinski compared upper extremity kinetics between spikes directed straight ahead and those driven across the body and reported few differences.[23] Although these studies are informative, they do not compare upper extremity biomechanics during various spiking and serving techniques. The hypothesis of the current study was that the kinetics and kinematics of the upper limb vary when performing different spikes and serves. In particular, shoulder kinetics and angular velocities should be greater in the harder spikes (straight-ahead and cross-body spikes) and faster serve (jump serve) than in the off-speed spike (roll shot) and the traditional float serve.

MATERIALS AND METHODS

Participants

The research protocol was approved by the Marshfield Clinic Research Foundation's Institutional Review Board. Fourteen healthy female National Collegiate Athletic Association Division 1 collegiate volleyball players provided their informed consent to participate in the study. They averaged 21 ± 2 years of age, 1.78 ± 0.08 m in height, and 72 ± 9 kg in mass. Thirteen athletes were right-hand dominant and 1 was left-hand dominant. A brief medical history was collected from each athlete to ensure her eligibility for the study. None of the athletes reported a history of shoulder or elbow surgery, and none complained of shoulder or elbow pain at the time of the testing.

Data Collection

Each athlete was required to wear tight-fitting clothing (ie, spandex shorts and a sleeveless shirt). Reflective markers (10 mm in diameter) were bilaterally attached to the surface of the skin over the following bony landmarks: acromion, lateral humeral epicondyle, ulnar styloid process, greater trochanter, lateral femoral epicondyle, lateral malleolus, and distal end of the third metatarsal. Additional reflective markers were attached to the dominant (striking) upper limb over the medial humeral epicondyle, the radial styloid process, and the distal end of the third metacarpal. Reflective markers on all volunteers were attached by one investigator (G.S.F.).

Data collection occurred in a large indoor biomechanics laboratory equipped with an 8-camera (240 Hz) 3-dimensional automatic digitizing system (Motion Analysis Corporation, Santa Rosa, California). A regulation-size volleyball court (18 × 9 m) was marked off in the lab, and a women's regulation-height net (2.24 m) was installed. The digitizing system was calibrated before each data collection session. Each athlete was encouraged to warm up according to her normal routine to ensure optimal performance. Once warmed up, each athlete performed a series of serves and spikes to the best of her ability. The order of skills was randomly assigned per athlete. For the spike trials, one investigator set the ball for the athlete. Three types of overhead attacks were performed: a cross-body/diagonal spike (with follow-through of the hitting arm across the athlete's midline), a straight-ahead spike (with follow-through of the hitting arm along the athlete's ipsilateral side), and an off-speed, cross-body roll shot. Previous research has shown low variability in overhead throwing biomechanics within individual college baseball pitchers, so we assumed that college volleyball players would likewise have low variability in their overhead motions.[16] Nevertheless, data for 5 trials were collected for each athlete for each type of spike. All athletes also performed 5 float serves. Those athletes who were competent at jump serving (n, 5) performed an additional 5 jump service trials.

Analysis of Kinematic and Kinetic Data

Three-dimensional marker locations were calculated with motion analysis software (EVaRT 5.0, Motion Analysis Corporation, Santa Rosa, California). Upper extremity kinematics were calculated as previously described.[10,14,17] Included were the displacement and velocity measurements of 3 shoulder angles (external rotation, horizontal adduction, and abduction) and 1 elbow angle (flexion).

Four kinetic values were calculated at the shoulder and elbow on the basis of kinematic data, documented cadaver body segment parameters, and inverse dynamics, as previously described.[14-17] Included were 2 forces (shoulder and elbow proximal force) and 2 torques (shoulder internal rotation torque and elbow varus torque). Kinetic values were expressed as the calculated loads applied at the joint by the proximal segment onto the distal segment. Kinetic values after ball contact were not calculated, because the kinetic model did not include the force generated by ball contact. Ball velocity was recorded with a Tribar Sport radar gun (Jugs Pitching Machine Company, Tualatin, Oregon) from a point directly in line with the anticipated trajectory of the volleyball.

The spike and the jump serve share a common motor pattern that has been divided into 5 phases based on the
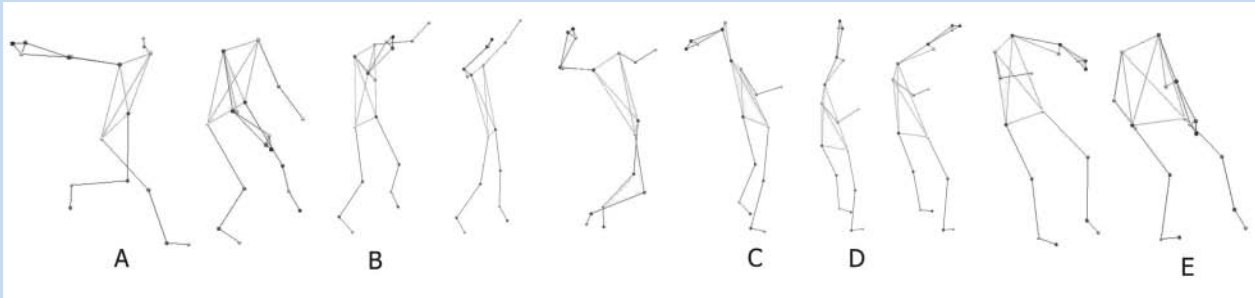
Figure 1. The 4 phases of the volleyball spike are the approach (A → B), arm cocking (B → C), arm acceleration (C → D), and follow-through (D → E). Key events during the volleyball spike or jump serve include: takeoff (B), maximum external rotation (C), and ball contact (D).

gross motor action: approach, takeoff, arm cocking, arm acceleration, and follow-through (Figure 1).[8] Arm cocking and arm acceleration are separated by the instant of maximum external rotation of the dominant shoulder. In anticipation of striking the volleyball, the athlete cocks her arm by abducting and externally rotating the dominant upper limb at the shoulder. During the acceleration phase, the attacker uncoils the upper limb (described as "cracking the whip") to contact the volleyball at the desired overhead position. At the moment of ball contact, the accelerating upper limb should be flexed and internally rotated at the shoulder and extended at the elbow. The forearm is pronated to a lesser or greater degree, depending on whether the athlete wishes to direct the ball diagonally across the body or straight ahead. The roll shot is used in indoor volleyball primarily as a tactical off-speed placement shot to catch the opponent off guard. Consequently, the athlete contacts the volleyball with similar mechanics but with considerably less force than if she were performing a hard spike. To compare our spiking and serving kinematic data, we divided each skill into the following phases: arm cocking, arm acceleration, and ball contact.

Statistics

A repeated-measures multivariate analysis of variance (MANOVA) was used to analyze kinetic differences among the cross-body spike, straight-ahead spike, roll shot, and float serve. A second MANOVA was used to analyze kinematic differences among these 4 skills. When a MANOVA showed significant difference, an analysis of variance (ANOVA) was then conducted for each parameter in the MANOVA. Jump-serve data were not included in the MANOVAs or ANOVAs, because of the low number of volunteers who performed the skill. Finally, when a significant difference was found for an ANOVA, a post hoc paired t test was performed for each pair of skills. An alpha level of .01 was considered a measure of statistical significance.

RESULTS

Kinetics

Table 1 presents the kinetic values for each skill. Maximum shoulder internal rotation torque and maximum elbow varus torque were produced near the time of maximum external rotation to decelerate arm cocking and initiate the arm's forward rotation. Maximum proximal forces were produced at the end of the arm acceleration phase to resist joint distraction. The MANOVA revealed significant differences, $F(12, 114) = 6.87$, $P < .01$, and the ANOVA showed that differences existed within each parameter. Post hoc analysis showed that the roll shot produced the smallest forces and torques at the shoulder and elbow. The float serve generated the next-smallest force values, significantly less than those of the cross-body spike and straight-ahead spike. The forces and torques during the jump serve appeared to be similar to values for the cross-body and straight-ahead spikes.

Kinematics

Table 2 summarizes the kinematic data. Seven kinematic parameters were measured for each skill. The MANOVA revealed significant differences, $F(21, 105) = 6.79$, $P < .01$, among the skills, and the ANOVA showed significant differences for each parameter.

Post hoc analysis showed that the roll shot differed significantly from the other skills, demonstrating less shoulder external rotation to cock the arm back and less elbow extension velocity and shoulder internal rotation velocity to strike the ball. At the instant of ball contact, the roll shot had the lowest ball speed, lowest shoulder abduction, and greatest shoulder horizontal adduction.

The float serve had the second-lowest elbow extension velocity, shoulder internal rotation velocity, and ball speed. At the instant of ball contact, elbow flexion was greater in the float serve and roll shot than in the cross-body and straight-ahead spikes.

Table 1. Kinetic parameters for each skill, at selected time points.

	Cross-body Spike n, 14	Straight-ahead Spike n, 14	Roll Shot n, 14	Jump Serve n, 5	Float Serve n, 14	P^a
Maximum external rotation						
Maximum shoulder internal rotation torque (N·m)	36.8 ± 9.1	36.7 ± 9.0	16.5 ± 7.6	40.3 ± 10.4	31.9 ± 8.2	< .001[b,c,d]*
Maximum elbow varus torque (N·m)	37.5 ± 9.2	37.8 ± 9.3	17.3 ± 7.7	43.3 ± 10.6	33.1 ± 7.8	< .001[b,c,d]*
Arm acceleration phase						
Maximum shoulder proximal force (N)	399 ± 64	412 ± 94	172 ± 83	358 ± 75	330 ± 63	< .001[b,c,d,e,f]*
Maximum elbow proximal force (N)	295 ± 63	312 ± 79	111 ± 60	277 ± 63	222 ± 40	< .001[b,c,d,e,f]*

[a]Analysis of variance and pairwise differences.
[b]Post hoc significant differences ($P < .01$) between cross-body spike and roll shot.
[c]Post hoc significant differences ($P < .01$) between straight-ahead spike and roll shot.
[d]Post hoc significant differences ($P < .01$) between roll shot and float serve.
[e]Post hoc significant differences ($P < .01$) between cross-body spike and float serve.
[f]Post hoc significant differences ($P < .01$) between straight-ahead spike and float serve.
*Significant difference ($P < .01$) among cross-body spike, straight-ahead spike, roll shot, and float serve.

No differences were found between the cross-body spike and the straight-ahead spike. The kinematics for the jump serve appear to be similar to those for the cross-body and straight-ahead spikes.

DISCUSSION

The roll shot generated significantly less shoulder force and torque than that of either the cross-body or straight-ahead spike, whereas the float serve appeared to generate less shoulder force and torque than that of the jump serve. Therefore, athletes who have shoulder discomfort, who are attempting to return from injury, or who simply wish to reduce their risk of shoulder injury from overuse may be well advised to warm up and practice using off-speed attacks. Athletes who are already adept at spiking may choose to warm up for competition mostly with roll shots, reserving their most powerful spikes and their greatest effort—and, thus, the greatest load on their shoulder—for game situations. Similarly, those athletes who are attempting to return from injury may be able to resume hitting roll shots before hitting spikes without overloading the shoulder and incurring increased risk of recurrent injury. Volleyball players who spike hard and often might also consider limiting the number of jump serves (particularly in practice) because chronic overload from repetitive jump serving could contribute to the risk of shoulder problems. If the volleyball player does not possess

a particularly effective jump serve, float serves may be safer. By limiting the number of repetitions of the most demanding overhead skills, volleyball players could reduce their risk of developing symptoms of shoulder overuse. Unfortunately, these biomechanical data do not determine an appropriate upper limit of repetitions.

Shoulder internal rotation torque and elbow varus torque for each overhead volleyball-specific skill in the present study were less than 50 N·m, a value identified by Dillman et al[11] as an empirical threshold for injury to the upper limb. In addition, the force and torque at the shoulder and elbow are lower in female volleyball athletes than the forces and torques produced by female baseball pitchers and female tennis players (Table 3).[6,13] This reduced load at the elbow may correlate with the relatively low risk of volleyball-related elbow injury. The National Collegiate Athletic Association's Injury Surveillance System data indicate that elbow injuries are common in baseball (especially in pitchers) and rare in volleyball.[1] These observations suggest that the load associated with a single repetition of the most demanding overhead volleyball skills (spikes and jump serve) is probably not sufficient to produce acute shoulder or elbow pathology in a healthy, well-rested athlete.

Although research suggests that the risk factors for shoulder problems—including preexisting injuries, technical errors, level of strength and conditioning, and underlying anatomy— are similar across various overhead sports,[3,4,19,20] the interaction

Table 2. Kinematic parameters for each skill, at selected time points.

	Cross-body Spike n, 14	Straight-ahead Spike n, 14	Roll Shot n, 14	Jump Serve n, 5	Float Serve n, 14	P [a]
Maximum external rotation						
Maximum shoulder external rotation (°)	160 ± 10	163 ± 10	129 ± 32	164 ± 11	158 ± 12	.001 [b,c,d]*
Arm acceleration phase						
Maximum elbow extension angular velocity (°/s)	1579 ± 194	1666 ± 205	1198 ± 216	1535 ± 286	1417 ± 251	< .001 [b,c,d,e,f]*
Maximum shoulder internal rotation angular velocity (°/s)	2444 ± 608	2594 ± 772	1315 ± 502	2505 ± 1005	1859 ± 623	< .001 [b,c,d,e,f]*
Ball contact						
Shoulder abduction angle (°)	130 ± 8	133 ± 7	122 ± 9	129 ± 11	133 ± 11	< .001 [b,c,d]*
Elbow flexion angle (°)	34 ± 10	34 ± 10	43 ± 12	48 ± 26	50 ± 17	< .001 [b,c,e,f]*
Shoulder horizontal adduction angle (°)	29 ± 14	33 ± 15	43 ± 15	23 ± 24	30 ± 16	< .001 [b,c]*
Post-Contact						
Ball speed (m/s)	15.7 ± 1.7	15.5 ± 2.0	8.9 ± 1.7	15.5 ± 1.7	14.1 ± 1.4	< .001 [b,c,d,e,f]*

[a]Analysis of variance and pairwise differences.
[b]Post hoc significant differences (P < .01) between cross-body spike and roll shot.
[c]Post hoc significant differences (P < .01) between straight-ahead spike and roll shot.
[d]Post hoc significant differences (P < .01) between roll shot and float serve.
[e]Post hoc significant differences (P < .01) between cross-body spike and float serve.
[f]Post hoc significant differences (P < .01) between straight-ahead spike and float serve.
*Significant difference (P < .01) among cross-body spike, straight-ahead spike, roll shot, and float serve.

between risk factors is undoubtedly unique to each sport. For example, these data indicate that the kinetics of spiking and serving may be less than that of tennis or baseball. However, the substantially greater shoulder abduction and horizontal adduction at ball contact during volleyball may be a risk factor for subacromial impingement or labral damage. Unfortunately, corresponding epidemiologic injury data are not available to permit these comparisons between sports. Any associations between injury risk and biomechanical parameters are therefore speculative at this point and should be confirmed through prospective research.

Another factor associated with injury and performance in overhead athletes is glenohumeral internal rotation deficit.[9,12,24,28,30] Recent studies by Schwab and Blanch[30] and Reeser et al[25] found that volleyball players have relatively minor deficits of passive glenohumeral internal range of motion (ie, less glenohumeral internal rotation deficit) on the dominant side: a mean deficit of approximately 10°. This value is considerably smaller than the 20° to 25° reported for baseball players.[4,9,24,28,30] Compared to baseball pitchers and tennis players, volleyball players generate smaller maximum external rotation angles (Table 3). In addition, volleyball players produce appreciably smaller shoulder internal rotation torques compared to those of baseball and tennis players.

Lower torque production during an athlete's development may result in less strain on the capsule and less humeral retroversion.[9,12,24,28,30] Also, when compared to pitching a baseball, spiking or serving a volleyball generates slower internal rotation angular velocities. These factors may result in less accumulated eccentric overload on the posterior shoulder girdle of volleyball athletes, which may in turn result in less glenohumeral internal rotation deficit over time in comparison to that of other overhead athletes.

Limitations of this study include the relatively small sample size (n, 14), single sex (female), single skill level, and narrow age range. Thus, the findings may not apply to all volleyball players. Another limitation was the use of surface markers for quantifying joint motion. However, to limit variability in marker placement, a single investigator attached all the markers on all the athletes. The effect of surface marker variability was further reduced by using a repeated-measures design to compare the skills within each participant. Because markers were not moved for anyone during the trials, the same marker locations were used for the joint biomechanics of all compared skills.

In summary, shoulder and elbow kinetics are greatest during the cross-body spike, straight-ahead spike, and jump serve. To reduce the risk of overuse injuries, players who spike often

Table 3. Biomechanical comparison of selected overhead skills in female athletes.

	Current Study: Volleyball		Chu et al[6]	Elliott et al[13]
	Cross-body Spike	Jump Serve	Baseball Pitch: Fastball	Tennis Serve
Skill/experience level	Collegiate	Collegiate	Elite	Olympic
Sex	Female	Female	Female	Female
Sample size	14	5	11	12
Ball speed (m/s)	16 ± 2	16 ± 2	27 ± 2	42 ± 4
Kinematics				
Maximum shoulder external rotation (°)	160 ± 10	164 ± 11	180 ± 10	172 ± 12
Maximum elbow angular velocity (°/s)	1579 ± 194	1535 ± 286	2060 ± 370	1510 ± 310
Maximum shoulder internal rotation angular velocity (°/s)	2444 ± 608	2505 ± 1005	5630 ± 1590	1370 ± 730
Shoulder abduction at ball contact or release (°)	130 ± 8	129 ± 11	89 ± 6	101 ± 11
Elbow flexion at ball contact or release (°)	34 ± 10	48 ± 26	31 ± 10	20 ± 4
Shoulder horizontal adduction at ball contact or release (°)	29 ± 14	23 ± 24	9 ± 8	5 ± 10
Kinetics				
Maximum shoulder proximal force (N)	399 ± 64	358 ± 75	510 ± 108	608 ± 110
Maximum elbow proximal force (N)	295 ± 63	277 ± 63	453 ± 60	N/A
Maximum shoulder internal rotation torque (N·m)	37 ± 9	40 ± 10	48 ± 11	65 ± 16
Maximum elbow varus torque (N·m)	38 ± 9	43 ± 11	46 ± 9	68 ± 16

may opt to limit the number of hard spikes and jump serves during warm-up and practice, using roll shots instead.

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