FACTORS RELATED TO THE DEVELOPMENT OF BALL SPEED AND TO THE INCIDENCE OF ONE-LEGGED LANDINGS IN THE FRONT-ROW VOLLEYBALL ATTACK

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A three-dimensional video analysis was used to identify factors related to the development of ball speed and to the incidence of one-legged landings in high-outside, front-row volleyball attacks. At ball contact, hand speed was 11.9±0.9 m·s-1 (mean±SD). Post-impact ball speed was 19.4±2.3 m·s-1. Shoulder and elbow rotations accounted for about 75% of hand speed at the instant of ball contact while the speed of the CM itself accounted for about 16% of hand speed. Trunk rotation and wrist rotation contributed 11% and 2% to hand speed, respectively. Attackers possessed forward somersaulting, counterclockwise twisting, and counterclockwise "cartwheeling" angular momentum that resulted in faster hand speeds at contact but also a tendency for one-legged landings. Unfortunately, factors contributing to one-legged landings could not be clearly identified.

KEY WORDS: volleyball attack, ball speed, landing.

INTRODUCTION: Success in spiking or attacking is directly related to team success in volleyball. Although little is known about the biomechanics of the volleyball attack, it can be argued that the development of ball speed is one of the primary factors that contribute to successful attacking. The harder the ball is attacked, the faster the ball will travel and the shorter the time opposing defenders will have to successfully keep the ball in play. As such, an understanding of the mechanical factors that contribute to the development of ball speed during the attack is of great interest to volleyball coaches and athletes. Unfortunately, in their attempts to maximize ball speed, many coaches advocate and many athletes adopt attacking techniques that result in precarious landing positions. Upon review of more than 100 hours of video-taped footage from elite level volleyball competitions, approximately 67% of all front row attacking attempts resulted in one-legged landings (Vint, unpublished data). Tillman et al. (2004) recently reported a 35% one-legged landing rate from 408 competitive volleyball attack jumps. Coleman found that during the 1991 World Student Games, over 90% of attack landings were one-legged (S. Coleman, personal communication, 7/3/01). All else being equal, athletes would be required to dissipate greater impact stresses during one-legged landings compared to two-legged landings. As a result, one-legged landings may predispose athletes to a greater risk of sustaining either acute or repetitive injuries to the lower extremity. Fatigue-related decrements in athletic performance may also be expected to arise from frequent one-legged landings.

The purpose of this study was twofold: 1) identify factors related to the development of ball speed and 2) identify factors related to the incidence of one-legged landings among elite female volleyball players performing high-outside, front-row attacks. Regarding the former, we anticipated that the in-flight speed of the CM and rotations of the elbow and shoulder would contribute most significantly to hand speed at impact and hence to ball speed after impact. Regarding the latter, it was hypothesized that one-legged landings would result from excessive lateral rotating or "cartwheeling" angular momentum that was generated during the ground support phase of the attack jump. While "cartwheeling" angular momentum would not appear to be necessary to achieve a desirable body position at the instant of ball contact, other angular momenta (i.e., "twisting" and "forward somersaulting") might contribute to the development of higher ball velocities during the attack.

METHODS

Subjects and testing arrangements: Nine members of the 1999 USA Volleyball A2 Women's National Team (mean age 20.1 ± 0.9 years, mean height 1.91 ± 0.07 m, mean mass 76.6 ± 6.3 kg) were filmed at the United States Olympic Training Center in Colorado Springs, Colorado. All subjects were right-handed and played as either an outside or middle attacker on their respective college teams. Data were collected during competitive drills in which outside attackers were required to hit a high-outside, front-row set against an imposing block.

Video and calibration: Two synchronized video cameras were used to obtain video images at 60 fields·s-1. Three-dimensional calibration was performed using a modified version the multiphase interpolation technique described by Challis (1995). Fifty-five control points were used to establish the final set of DLT camera parameters. The mean resultant, re-predicted control point accuracy was 5.7 mm (0.13% maximum diagonal).

Data reduction: Thirty-two trials, comprising 16 one-legged landings and 16 two-legged landings, identified from the nine participating athletes were used in the final analysis. Although multiple trials were analyzed from each participating athlete, each trial was considered as an independent observation in the subsequent analyses.

Two-dimensional video images from each camera were digitized from the beginning of the approach until the instant of landing. Twenty-one anatomical landmarks were digitized to define a 14-segment model of the human. When in view, the center of the ball was also digitized. The DLT algorithm was used to reconstruct three-dimensional coordinates from the digitized two-dimensional video images. Coordinates of each digitized landmark, except the ball, were smoothed with a second-order, zero-lag, Butterworth digital filter. Cutoff frequencies for each coordinate of each digitized landmark were independently selected using the autocorrelation-based procedure described by Challis (1999). Velocity data were computed using the smoothed coordinate data and a standard numerical differentiation equation and were not subject to further smoothing.

Approach, takeoff, and ball velocity: Horizontal approach velocity of the athlete's CM was calculated during the in-flight phase of the approach prior to the final foot plant of the attack jump. The takeoff velocity of the athlete's CM was calculated using 3D velocity components at the instant of takeoff into the attack jump. Two takeoff velocity angles were calculated: an "elevation" angle and a "cross-court" angle. Resultant 3D ball velocity was calculated using three to six frames immediately following ball contact. Two relevant ball velocity components were calculated: a "downward" angle and a "cross-court" angle.

Angular momentum: Segmental and whole body angular momenta were computed from methods described by Hinrichs (1987) and Chung (1988, 1990). The overall angular momentum of the "arms" separately was calculated for each frame by adding together the angular momentum terms for the left and right upper arms, forearms, and hands. The whole body angular momentum was calculated for each frame by summing the angular momentum terms over all segments. Angular momentum terms were normalized by dividing the absolute values of angular momentum (expressed in kg·m2·s-1) by the athlete's body mass (in kg) and by the square of the athlete's standing height (in m). Angular momentum from the arms was calculated by averaging the angular momentum values over the double-support phase prior to the attack jump takeoff. The component of most interest (Harms_Z, that due to the flexion and extension of the shoulder), was expressed in a coordinate system established by the direction of the athlete's CM velocity vector at the instant of takeoff. The angular momentum of the whole body was calculated by averaging the angular momentum values over the flight phase of the attack jump, up to, but not including, the instant of ball contact. Twisting, somersaulting, and cartwheeling components of the whole body angular momentum were estimated by expressing the whole body angular momentum vector in coordinate systems established by (1) the global coordinate system; (2) the direction of the athlete's CM velocity vector at the instant of takeoff projected onto the horizontal plane; and (3) the direction of the velocity vector of the ball immediately after impact projected onto the horizontal plane.

Segmental contributions to hand speed at contact: Segmental contributions to the speed of the hand at the instant of contact were quantified using methods adapted from Chung (1988, 1990). All segment contributions were originally computed in the global coordinate system. However, in order to describe the contributions of each segment rotation to the velocity of the hand, each contribution vector was projected onto the velocity vector of the hand.

Statistical analyses: Pearson's product moment correlations were used to assess the strength of relationships between several variables related to the development of ball speed, and to the in-flight angular momentum. Independent t-tests were used to determine if angular momentum components were associated with the incidence of one-legged landings (the incidence of one-legged landings served as a grouping variable). An alpha level of .05 was selected for all statistical tests.

RESULTS AND DISCUSSION:

Approach, takeoff, and ball velocity: Resultant horizontal approach speed of the CM ranged from 2.9 to 4.1 m·s-1 while resultant (3D) takeoff speed ranged from 2.8 to 3.8 m·s-1. Mean cross-court angles of approach and takeoff were highly variable at 26.8±10.5 degrees and 15.4±15.4 degrees, respectively. Elevation angle of the CM at takeoff ranged from 42.4 to 68.7 degrees with an average value of 58.5±6.4degrees. Ball speeds ranged from 13.8 to 23.5 m·s-1. Balls were directed 38.4±14.8 degrees toward the middle of the court (with respect to the left sideline) and -16.4±6.2 degrees downward (with respect to the horizontal). Hand speed at impact was significantly correlated with resultant approach and takeoff speeds ($r=0.54$, $p<0.01$; $r=0.42$, $p<0.05$, respectively), but was not correlated with ball speed ($r=.27$, $p=.13$). It is possible that the lack of correlation between hand and ball speed was attributable to the relative homogeneity of the data.

Angular momentum: Regardless of the reference frame in which the values were expressed, athletes generally possessed forward somersaulting and negative cartwheeling angular momentum. Negative cartwheeling angular momentum indicated that the athletes would tend to land on their left leg. As hypothesized, there was a significant negative correlation between forward somersaulting angular momentum and horizontal approach velocity (rglobal=-0.72; rcm_vel=-0.64; rball_vel=-0.66; all $p<0.01$). This association meant that greater horizontal approach speed resulted in greater forward somersaulting angular momentum. Unfortunately, this was the only notable correlation that was identified between angular momentum and approach or takeoff parameters. Mean normalized angular momentum for the arms during double-support was 17.9±7.0 10-3s-1. The positive value meant that the arms contributed a backward somersaulting angular momentum during the double-support phase of the approach. This was not significantly correlated with flight height ($r=-0.17$; $p=0.37$) or takeoff height ($r=0.13$; $p=0.48$). Somersaulting angular momentum of the arms was also uncorrelated with whole body somersaulting angular momentum ($r=0.32$; $p=0.07$), although greater backward somersaulting angular momentum from the arm swing during the approach tended to reduce the magnitude of the forward somersaulting angular momentum of the whole body during flight.

Segmental contributions to hand speed at contact: Segmental contributions to hand speed at the instant of contact were dominated by elbow (44.9%) and shoulder (30.5%) rotation. The velocity of the CM itself (15.6%) had the next highest contribution followed in order by trunk rotation (10.8%) and wrist rotation (2.1%). The relative velocity of the trunk CM with respect to the body CM had a negative contribution to ball speed (-2.7%). The error in estimating the velocity of the CM of the hand was less than 2%. The only segmental contribution that was significantly correlated with hand speed at the instant of ball contact was CM speed ($r=0.46$, $p<0.01$).

Effects of angular momentum on landing position and hand speed: It was hypothesized that the incidence of one-legged landings would be associated with cartwheeling angular momentum. To test this, trials were grouped by landing type, onelegged or two-legged, and independent t-tests were performed using the three reference frame expressions of cartwheeling angular momentum (global, CM velocity vector, ball velocity vector). Results from the statistical analyses indicated that, regardless of coordinate system, there was cartwheeling angular momentum that would in fact cause athletes to land on their left leg, but these values were not different between one-legged and two-legged landings. Average cartwheeling angular momentum values for one- and two-legged landings were, respectively, -15.5±11.1 and -11.3±9.5 10-3·s-1 [$t(30)= -1.15$; $p=0.26$]; when expressed in the global reference frame; -25.5±12.5 and -21.6±9.4 10-3·s-1 [$t(30)=-0.99$; $p=0.32$] when expressed in the reference frame defined by the velocity vector of the CM at takeoff; and -34.6±10.3 and -28.7±10.3 10-3·s-1 [$t(30)=-1.62$; $p=0.12$] when expressed in the reference frame defined by the velocity vector of the ball immediately after contact. No other differences between one-legged and two-legged landings were identified. This included foot, hip and shoulder position at takeoff, approach speed and direction, and takeoff speed and direction. It was also hypothesized that hand speed would be correlated with twisting and forward somersaulting angular momentum but would be unrelated to cartwheeling angular momentum. These results were confirmed. Correlations between hand speed and twisting, somersaulting, and cartwheeling whole body angular momentum were 0.49 ($p<0.01$), -0.50 ($p<0.01$); and 0.09 ($p=0.62$) when expressed in a reference frame defined by the velocity vector of the ball at impact. The negative correlation between somersaulting angular momentum and hand speed meant that greater hand speeds were associated with higher forward somersaulting in-flight angular momentum values.

DISCUSSION AND IMPLICATIONS FOR PERFORMANCE: Horizontal approach speed was significantly correlated with forward somersaulting angular momentum and hand speed at the instant of ball contact. Therefore, faster approaches appeared to be beneficial to several important aspects of attacking performance. Once in flight, athletes possessed forward somersaulting, counterclockwise twisting, and a cartwheeling angular momentum that would tend to predispose right-handed attackers to land on their left leg. Unfortunately, while forward somersaulting and twisting angular momentum values were significantly correlated with hand speed, it was not possible to identify any factors related to the incidence of one-legged landings. Segmental contributions to hand speed at the instant of ball contact were similar to those reported by Chung (1988, 1990). Elbow and shoulder rotations accounted for more than 75% of the speed of the hand at impact. The speed of the whole body CM and the rotation of the trunk at impact were also major contributors, accounting for about 16% and 11% of hand speed, respectively. The relatively high variability found in the contributions of trunk, shoulder, and elbow rotation may indicate that there can be a considerable amount of exchange between these segments in terms of their contributions to hand speed at impact. Interestingly, the only significant correlate to the hand speed at impact was the speed of the whole body CM. Since the speed of the CM is primarily derived from the speed of the horizontal approach, this highlights the importance of approach speed in the front-row volleyball attack.

REFERENCES:

Challis, J.H. (1995). A multiphase calibration procedure for the direct linear transformation. Journal of Applied Biomechanics, 11 (3), 351-358.

Challis, J.H. (1999). A procedure for the automatic determination of filter cutoff frequency for the processing of biomechanical data. Journal of Applied Biomechanics, 15, 303-317.

Chung, C.S. (1988). Three-dimensional analysis of the shoulder and elbow during the volleyball spike. Unpublished doctoral dissertation, Indiana University, Bloomington, IN.

Chung, C.S. (1990). Three-dimensional kinematics of the striking arm during the volleyball spike. Korean Journal of Sport Sciences, 2, 124-151.

Hinrichs, R.N. (1987). Upper extremity function in running II: Angular momentum considerations. International Journal of Sport Biomechanics, 3, 242-263.

Tillman, M.D., Hass, C.J., Brunt, D., & Bennett, G.R. (2004). Jumping and landing techniques in elite women's volleyball. Journal of Sports Medicine and Science, 3, 30-36.

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