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Three-Dimensional Kinematics of the Striking Arm during the Volleyball Spike

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The purpose of this study was to investigate the patterns of motion of the striking arm during the arm swing phase of the volleyball spike.

Seven elite male volleyball players served as subjects. The subjects were filmed using the Direct Linear Transformation (DLT) method of three-dimentional (3D) cinematography, and film analysis procedures were used to obtain 3D coordinates of the ball and of 21 body landmarks. The kinematic parameters investigated were the temporal phases of the spike, the ball speed, the speed of the hand and the contributing factors, and the angular positions and angular velocities of the shoulder and elbow joints.

During the backswing phase, most subjects had the arm motion of elbow flexion, horizontal abduction and external rotation at the shoulder, and no elevation at the shoulder. During the forward swing phase, the arm motion was dominated by elbow extension, horizontal adduction and elevation at the shoulder. The speed of the hand during the forward swing phase was contributed by the descending order of the somersault rotation at the shoulder, the twisting of the trunk, the elbow extension, the velocity of the center of mass of the body, and the forward rotation of the trunk.

INTRODUCTION

The spike is one of the most important skills in volleyball, and it is one of the most difficult to perform correctly. A successful spike is determined primarily by three factors : (1) the position of the ball at impact, (2) the speed of the ball after impact, and (3) the direction of movement of the ball after impact. Of these three factors, the speed and direction of movement of the ball after impact are determined primarily by the velocity of the hand just prior to the instant of contact. The velocity of the hand can be considered the sum of the velocities of the center of mass (c.m.) of the body and of the hand relative to the c.m. of the body. The relative velocity of the hand is determined by the motions of the striking arm and of the remaining body segments during the spike.

The spiking motion was divided into four major temporal periods : approach run, takeoff, striking and recovery phases. The striking phase was subdivided into the arm swing and impact phases. The arm swing phase was further subdivided into backswing and forward swing phases. The backswing phase was defined as the period from takeoff from the floor to the instant of maximum horizontal abduction at the shoulder of the striking arm. The forward swing phase was defined as the period from the end of the backswing phase to the first instant of contact with the ball. This project concentrated mainly on the mechanics of the striking arm during the arm swing phase of the volleyball spike, which was defined as the period from the instant when both feet leave the floor to the instant when the hand contacts the ball.

A considerable amount of literature has described the motion of the striking arm during the volleyball spike, but very few of these studies have been scientific. Most studies have been subjective analyses by coaches, teachers or players. Furthermore, the few scientific studies of the volleyball spike have been 2D analyses, which cannot provide the information necessary to explain the movement patterns of the markedly 3D motions that the striking arm executes during the arm swing phase. Only the studies by Loye (1978) and Chung (1988) used 3D analysis. Loye (1978) described the motions of three female U.S.A. Olympic volleyball players performing the deep cross court spike. However, she expressed the motion at the shoulder joint of the striking arm in terms of a reference frame that was not anatomically relevant, and this made her results difficult to interpret. Chung (1988) investigated the 3D kinematics and kinetics of the striking arm during the arm swing phase of the volleyball spike. The subject of the study was limited to the female collegiate volleyball players. Accordingly, the biomechanical information of the striking arm during the arm swing phase of the volleyball spike has been incomplete. The present study was essentially a supplement of the previous study (Chung, 1988), using male elite volleyball players as subjects.

The main goal of the present study was to investigate the 3D patterns of motion of the striking arm during the arm swing phase of the volleyball spike. The kinematic parameters investigated were the temporal phases of the striking arm, the velocity immediately after impact, and the linear velocities of each body landmark, of the c.m. of each segment, and of the c.m. of the whole body. The contributions to the speed of the c.m. of the hand by the linear velocity of the c.m. of the body, the linear velocity of the c.m. of the trunk relative to the c.m. of the body, the angular velocity of the trunk, and the angular velocities at the shoulder, elbow, and wrist joints were also investigated. The angular position and angular velocity values of the shoulder and elbow joints of the striking arm were also measured. The results of this investigation are expected to help volleyball coaches and players to understand in greater detail the mechanics of the striking arm, which can be useful for the improvement of performance and for the prevention of injuries.

METHOD

The deep cross-court spikes of seven male semi-professional volleyball players were studied using the 3D filming method. The average height and weight of the subjects were 1.93 m and 84 kg (Table 1). The subjects were filmed during a normal practice session with two Photosonic motion picture cameras set at nominal frame rates of 200 fps. (Actual frame rates were determined afterwards using timing lights.) One camera viewed the subjects from the rear and the other, from the spiking arm side. The subjects wore no shirts and, to aid in digitizing the elbow and wrist joints, a black band was painted around each of these joints with water paint. Three spikes of each subject were filmed, but for analysis only the best trial of each subject was selected based on the speed of the ball after impact.

Table 1. Standing heights and masses of the subjects.

Subject	Trial #	Height (m)	Mass (kg)	Age
1	8	1.97	87	20
2	9	1.90	80	28
3	10	1.95	83	27
4	13	1.93	82	23
5	14	1.87	80	23
6	15	1.95	95	23
7	20	1.95	83	25
Mean		1.93	84	24
S.D.		0.04	5	3

To calculate the 3D coordinates, it was first necessary to find the correspondence between the frames of two cameras for each trial. The corresdence was achieved through events visible in both films following a procedure described by Dapena (1984). The frames of occurrence of the events in the films of the two cameras were estimated to the nearest tenth of a frame by direct observation of the films. These values were then plotted against each other, and a straight line was fitted through the points by linear regression. Its equation defined the correspondence between the frames of the two cameras.

A Vanguard projection head was used to project the film image onto a Calcomp 9100 digitizer, connected to a Acer IBM-AT compatible personal computer. The coordinates of 21 body landmarks and the center of the ball were digitized in the projected film images for every frame of the two cameras, from the instant approximately 10 frames prior to take-off to the instant approximately 10 frames after ball contact.

Due to the absence of mechanical synchronization of the cameras, the instants of exposure of the frames in one film did not conincide exactly with the instants of exposure of frames in the other film. Quintic spline functions (developed by Wood and Jennings (1979), and reported in detail bv Vaughan (1980)) were fitted, with no smoothing, to the film coordinate-time data obtained from each camera. Subsequently, the quintic spline functions were used to compute interpolated values for times intermediate between frames, and that corresponded in the two cameras ; the precise correspondence of these instants was determined using the equation for frame correspondence, obtained previously. For convenience, and to facilitate comparisons among trials, the interpolated values were computed for instants separated by intervals of exactly 0.005 s ("output frames"), and the time t = 10.000 s was arbitrarily assigned to the instant of impact with the ball. (This was only an initial choice for the times of the output frames.)

The DLT method (Abdel-Aziz & Karara, 1971 ; Walton, 1981) was used to compute 3D coordinates of the center of the ball and

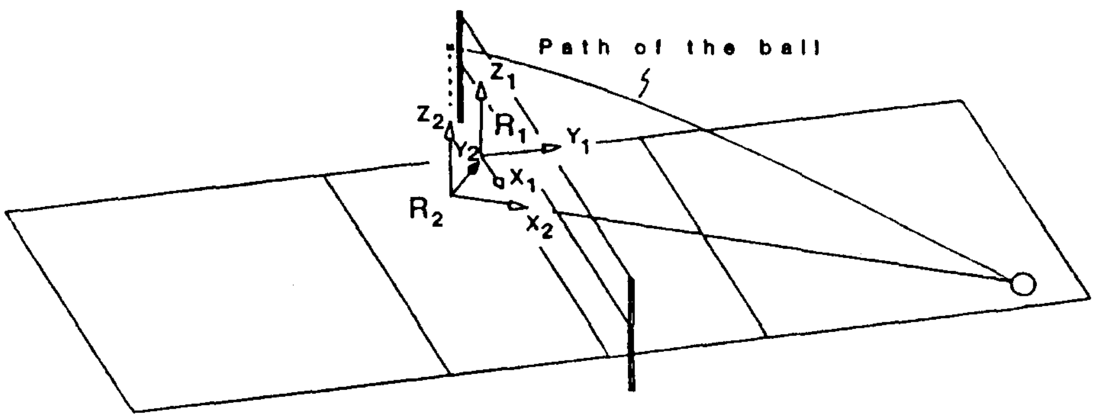

Figure 1. Reference Frame R_1 and R_2.

of the body landmarks for the time of each out-put frame in terms of a right-handed, inertial reference frame R_1 (Figure 1). The X_1 axis was horizontal and directed along the center line of the volleyball court; Y_1 axis was horizontal and directed toward the opponent's court along the sideline of the court; the Z_1 axis was vertical.

Quintic splin functions were used to smooth the time-dependent coordinates of each landmark. However, it was not possible to find the appropriate smoothing factor with the shoulder torque data of 0.005 s interval. It was difficult to avoid oversmoothing the data before reaching a smoothing factor large enough to produce reasonably smooth plots for the torque values. To solve this problem, the time-dependent data of 0.020 s interval including the value at $t = 9.995$ s were extracted from the 0.005 interval data and were smoothed for the analysis, following the prodedure explained by Chung (1988). To avoid the systematic bias resulting from using any data after impact, conditions immediately before impact ($t = 10.000$ s) were inferred by expolation using the quintic spline coefficients from the previous interval ($t = 9.975 - 9.995$ s). These smoothed 3D location values were used for all subsequent computation. The first derivatives of the quintic spline function yielded instantaneous values for the velocity of the landmarks.

To define the temporal periods of the arm swing during the spike, the times of occurrence of the events were determined. The time $t = 10.000$ s was arbitrarily assigned to the first instant of contact with the ball. The instant of takeoff was determined through direct observation of the film, and the instants of maximum horizontal abduction at the shoulder was calculated using the 3D landmark data.

The positions of the ball in several frames after impact with the hand were used to calculate the X, Y and Z components of the ball velocity immediately after the end of impact. In order to obtain more points available, 3D coordinates of the ball at 0.005 s intervals were used. The ball velocity was calculated using linear regression for the horizontal components (X and Y) and the parabola equation for the vertical component (Z) following a procedure described by Chung (1988). The magnitude of the ball velocity immediately after impact was computed from the three components of the ball velocity.

Each subject was modeled as a mechanical system composed of 14 segments (Dapena, 1978). Segmental masses and c.m. locations were taken from Dempster's (1955) cadaver data, except for the head-and-trunk segment, which was separated into two segments (head and trunk) according to the propotions given by Clauser et al. (1969). The 3D components of the c.m. location were computed from the landmark coordinates following a procedure described by Dapena (1978). The components of the c.m. velocity were computed from the landmark velocities using the same procedure.

All calculations were performed in terms of the reference frame R_1, but two other reference frames were also used to describe the linear kinematics (R_2) and to express the angular kinematics of the shoulder joint (R_3). An inertial, right-handed orthogonal reference frame R_1 was defined relative to the horizontal direction of the ball after impact (Figure 1). X_2 was horizontal and was in the direction of the horizontal component of the ball after impact ; Z_2 was vertical ; Y_2 was determined by the cross product of Z_2 and X_2. To aid in the calculation of the elevation, horizontal abduction-adduction and

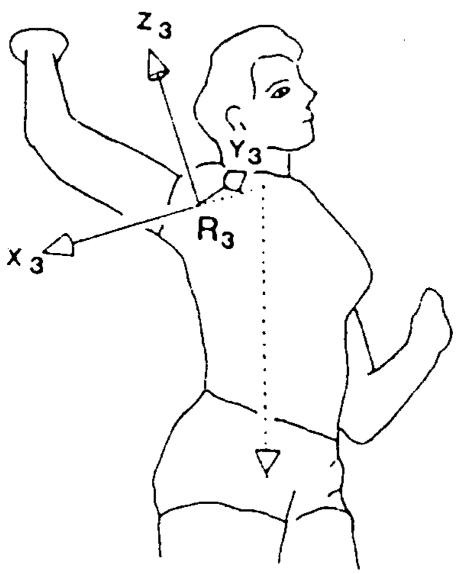

Figure 2. Reference Frame R_3.

internal-external rotation angles at the shoulder joint, a non-inertial reference R3 was defined (Figure 2).

The elevation, horizontal abduction-adduction and internal-external rotation angles at the shoulder, and the flexion-extension angle at the elbow were calculated to describe the pattern of the spiking arm. To determine these four angles, it was necessary to define vectors v_1 and v_2, that coincided, respectively, with the longitudinal axes of the upper arm and the forearm : Vector v_1 pointed from the shoulder joint to the elbow joint ; v_2 pointed from the elbow joint to the wrist joint. The elevation angle at the shoulder was calculated as the angle formed by vectors v_1 and v_3, where v_3 was the projection of v1 on the plane defined by the X_3 and Y_3 vectors. The horizontal abduction-adduction angle at the shoulder was calculated as the angle formed by vectors X_3 and v_3. The angle for internal-external rotation at the shoulder joint was calculated as the angle formed by vectors v_4 and v_5, where vectors v_4 and v_5 were, respectively, as the projections of v_2 and direction vector Z_3 of reference frame R_3 on the plane perpendicular to the longitudinal axis of the upper arm. The angle of flexion-extension at the elbow joint was calculated as the angle formed by vectors v_1 and v_2. To calculate instantaneous joint angular velocities, quintic spline functions were fitted to time-dependent angle data with no smoothing. The first derivative of the functions provided the joint angular velocity values.

Breakdown of the speed of the hand into contributing factors was done using a procedure described by Chung (1988). The velocity of the hand (V_{HD}) can be separarted into contributing factors using the following equation :

$$
\begin{aligned}
V_{HD} = {} & V_G + \\
& V_{TK/G} + \\
& W_{TK/GR} \times r_{HD/TK} + \\
& W_{UA/TK} \times r_{HD/SH} + \\
& W_{FA/UA} \times r_{HD/ELB} + \\
& W_{HD/FA} \times r_{HD/WR} + \\
& (V_{SH/TK})_{rad} + (V_{ELB/SH})_{rad} + (V_{WR/ELB})_{rad} + (V_{HD/WR})_{rad}
\end{aligned}
$$

where V_G and $V_{TK/G}$ were, respectively, the velocities of the c.m. of the whole body and of the c.m. of the trunk relative to the c.m. of the whole body ; $W_{TK/GR}$, $W_{UA/TK}$, $W_{FA/UA}$ and $W_{HD/FA}$ were the angular velocities of the trunk, of the upper arm relative to the trunk, of the forearm relative to the upper arm, and of the hand relative to the forearm, respectively ; $r_{HD/TK}$, $r_{HD/SH}$, $r_{HD/ELB}$, $r_{HD/WR}$ were the location vectors of the hand relative to the trunk, the shoulder, the elbow, and the wrist, respectively ; $(V_{SH/TK})rad$, $(V_{ELB/SH})rad$, $(V_{WR/ELB})rad$, $(V_{HD/WR})rad$ were the radial components of the relative velocities of the shoulder with respect to the c.m. of the trunk, of the elbow with respect to the shoulder, of the wrist with respect to the elbow, and of the c.m. of the hand with respect to the wrist.

V_G was defined as the contribution to the velocity of the hand by the velocity of the c.m. of the whole body ; $V_{TK/G}$ was the contribution by the velocity of the c.m. of the trunk relative to the c.m. of the whole body ; the $W_{TK/GR} \times r_{HD/TK}$ term was the contribution by the trunk rotation ; the $W_{UA/TK} \times r_{HD/SH}$ term was the contribution by the shoulder ; the $W_{FA/UA} \times r_{HD/ELB}$ term was the contribution by the elbow ; the $W_{HD/FA} \times r_{HD/WR}$ term was the contribution by the wrist ; and the $(V_{SH/TK})rad + (V_{ELB/SH})rad + (V_{WR/ELB})rad + (V_{HD/WR})rad$ term was the contribution by the non-rigidity of the segments and by errors.

The contribution by the trunk rotation was further divided into the contributions made by the twist rotation, the forward or backward somersault rotation, and the lateral somersault rotation of the trunk. To calculate the above parameters, the angular velocity of the trunk relative to the ground ($W_{TK/GR}$) was separated into three components by projecting it onto three vectors defined relative to the position of the upper trunk ; The longitudinal component ($W_{TKL/GR}$) was its projection onto a vector pointing along the longitudinal axis of the trunk, and it defined the twist rotation of the trunk ; the frontal component ($W_{TKF/GR}$) was its projection onto a vector determined by the cross product of a vector pointing along the longitudinal axis of the trunk with a vector joining both shoulders, and it defined the lateral somersault rotation ; and the transverse vector ($W_{TKT/GR}$) was its projection onto a vector perpendicular to the longitudinal and frontal components, and it defined the forward or backward somersault rotation. The three components of the angular velocity of the trunk relative to the ground were applied to the $W_{TK/GR} \times r_{HD/TK}$ term :

$$W_{TK/GR} \times r_{HD/TK} = (W_{TKL/GR} \times r_{HD/TK}) + (W_{TKF/GR} \times r_{HD/TK}) + (W_{TKT/GR} \times r_{HD/TK})$$

The $(W_{TKL/GR} \times r_{HD/TK})$, $(W_{TKF/GR} \times r_{HD/TK})$ and $(W_{TKT/GR} \times r_{HD/TK})$ terms were defined as the contributions to the velocity of the hand by the twist rotation, the lateral somersault rotation and the forward or backward somersault rotation of the trunk, respectively.

The contribution by the shoulder was also further divided into the contributions made by the somersault rotation and the twist (internal-external) rotation of the upper arm. To calculate the subdivided contributions, the angular velocity of the upper arm relative to the trunk ($W_{UA/TK}$) was separated into two components : The longitudinal component($W_{UAL/TK}$) was determined by projecting the relative angular velocity on the longitudinal axis of the upper arm, and it defined the twist rotation of the upper arm (internal-external rotation at the shoulder) ; and the transverse component($W_{UAT/TK}$) was determined by subtracting $W_{UAL/TK}$ from $W_{UA/TK}$. The two components of the angular velocity of the upper arm relative to the trunk were applied to the $W_{UA/TK} \times r_{HD/SH}$ term :

$$W_{UA/TK} \times r_{HD/SH} = (W_{UAL/TK} \times r_{HD/SH}) + (W_{UAT/TK} \times r_{HD/SH})$$

The $(W_{UAL/TK} \times r_{HD/SH})$ and $(W_{UAT/TK} \times r_{HD/SH})$ terms were defined, respectively, as the contributions to the velocity of the hand by the twist rotation and the somersault rotation of the upper arm at the shoulder joint.

All the contributions were computed in terms of the reference frame R_1. Then, each contribution vector was projected onto the velocity vector of the hand in each output frame. The magnitude of each projection indicated the contribution to the speed of the hand (a positive sign was given when the projection of the vector pointed to the same direction as the velocity vector of the hand ; a negative sign, when it pointed to the opposite direction.)

Some other kinematic parameters such as the ball position relative to the shoulder at the instant of ball contact, the horizontal and vertical components of the velocity of the c.m. of the whole body, the takeoff angle, the heights of the c.m. of the whole body at the instants of takeoff, peak, and ball contact were calculated following procedures described elsewhere (Chung, 1988).

RESULTS AND DISCUSSION

Temporal periods of the spike

The time of occurrence of the events used to define the temporal periods of the arm swing and the duration of each phase are

Table 2. Times of events defining the temporal periods, and durations of the periods.(TO = takeoff; MHA = maxium horizontal abduction; BC = ball contact; BS = back swing phase; FS = forward swing phase ; AS = arm swing phase).

Subject		Time			Duration (s)	
	TO	MHA	BC	BS	FS	AS
1	9.660	9.940	10.000	0.280	0.060	0.340
2	9.675	9.930	10.000	0.255	0.070	0.325
3	9.614	9.910	10.000	0.296	0.090	0.386
4	9.600	9.868	10.000	0.268	0.132	0.400
5	9.629	9.851	10.000	0.222	0.149	0.371
6	9.522	9.842	10.000	0.320	0.158	0.478
7	9.653	9.949	10.000	0.296	0.051	0.347
Mean	9.622	9.899	10.000	0.277	0.101	0.378
S.D.	0.051	0.044	0.000	0.032	0.044	0.051

All values have been rounded off to the nearest 0.001 s.

presented in Table 2. TO, MHA, and BC indicate the instants of takeoff, maximum horizontal abduction at the shoulder joint, and ball contact, respectively. The three phases presented in Table 2 are the backswing phase (BS), the forward swing (FS), and the sum of both phases, the arm swing phase (AS). The instant of maximum horizontal abduction at the shoulder separated the backswing phase from the forward swing phase.

For the subjects ($N = 7$), the times of events for the temporal periods were 9.622 ± 0.051 s for TO, 9.899 ± 0.044 for MHA, and 10.000 ± 0.000 s for BC. The durations of the temporal periods were 0.277 ± 0.032 s for BS, 0.101 ± 0.044 s for FS, and 0.378 ± 0.051 s for AS. Since Chung (1988) has separated FS from BS at the instant of maximum external rotation at the shoulder, it is not possible to compare the durations of BS and FS of this study with the corresponding data of Chung (1988). However, the duration of AS of the present study was 0.038 s longer than the corresponding data (0.340 ± 0.030 s) of the female subjects of Chung (1988).

Ball speed

The speed of the hand immediately before ball contact and the speed of ball immediately after impact are presented in Table 3. The speed of the hand was 21.40 ± 2.71 m/s ; the speed of the ball was 25.69 ± 1.28 m/s. Figure 3 shows a plot of the ball speed against the speed of the hand. The diagonal reference line indicates the points for which the two values would be equal. The positions of the points, generally higher than the diagonal reference line, indicate that the speed of the ball was somewhat faster than the speed of the hand. The correlation coefficient between the two parameters was not high enough to indicate that the speed of the hand was a good predictor of the speed of the ball ($r = 0.44$). It could have been due to the small number of subjects. When compared with female subjects of the previous study (Chung, 1988), the male subjects of this study had faster speed of the hand by 3.6 m/s and by 6.94 m/s for the speed of the ball faster.

Table 3. Comparison between the speed of the hand immediately before impact and the speed of the ball immediately after impact.

Subject	Speed (m/s) Hand	Ball
1	20.05	26.21
2	19.57	24.03
3	20.85	27.12
4	24.11	25.06
5	22.83	25.35
6	25.01	27.45
7	17.38	24.61
Mean	21.40	25.69
S.D.	2.71	1.28

All values have been rounded off to the nearest 0.01 m/s.

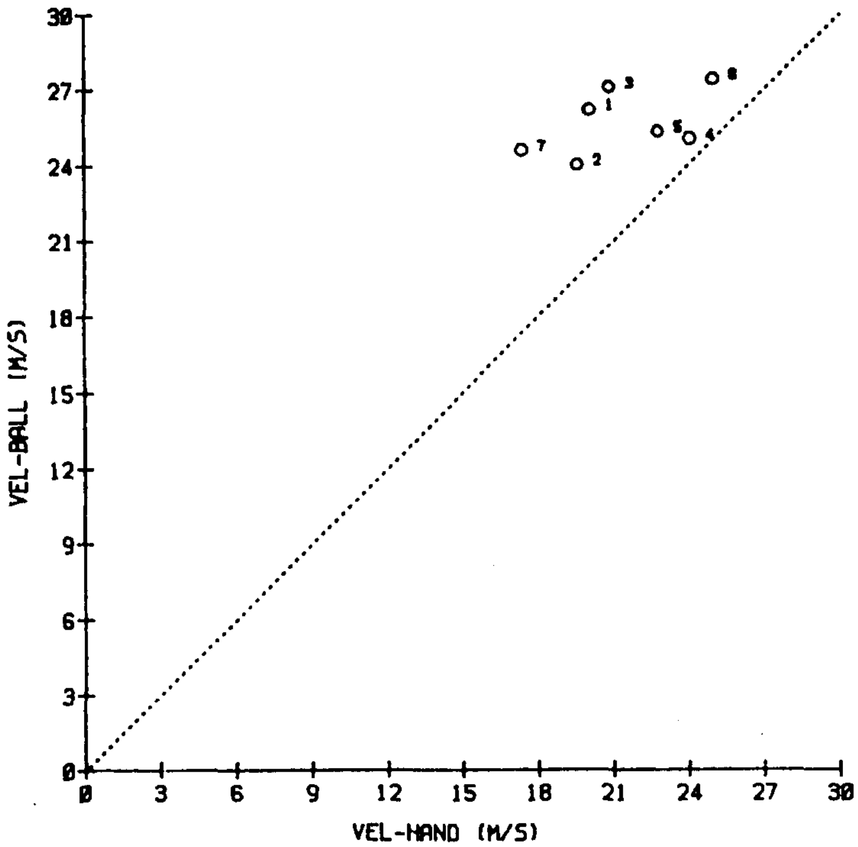

Figure 3. Relationship between speed of the hand and the ball

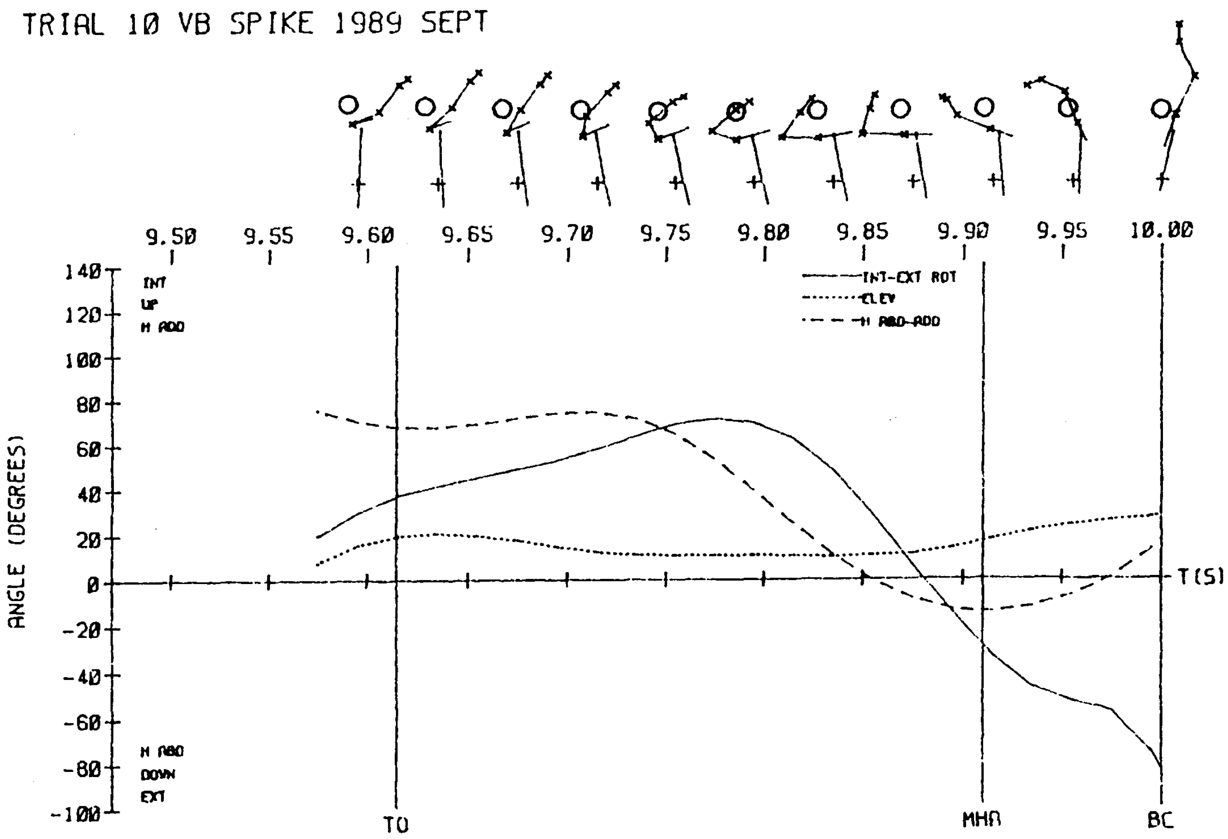

Figure 4. Angular positition at the shoulder.

Joint angles and angular velocities

The three shoulder angles that determined the position of the upper arm relative to the upper trunk (the angles of internal-external rotation, horizontal abduction-adduction, and elevation) and the elbow angle were calculated and plotted against time (Figures 4 and 5). The positive values of these angles indicate that the arm rotated internally, adducted horizontally and elevated above the plane defined by vectors X_3 and Y_3 (Refer to Figure 3). The stick figurtes at the top show a side view (seen from the negative Y_2 direction) ; the x symbols in the figure indicate joints on the right side of the body, and the cross symbol indicates the c.m. of the body. The patterns of the arm motion during the arm swing phase were similar for all subjects, but the patterns of internal-exrenal rotation at the shoulder during the forward swing phase were different among the subjects.

During the backswing phase, all subjects horizontally abducted the arm, maintained the elevation angle relatively constant, and rotated the upper arm externally for a short period after the takeoff and then rotated internally. During the forward swing phase, all subjects horizontal adducted and elevated the arm. However, the patterns of internal-external angle during the forward swing phase were different among the subjects. Some subjects showed slight internal rotation of the upper arm, while others kept rotating the upper arm externally.

The patterns of the flexion-extension angle at the elbow during the arm swing phase were also similar for all subjects except subject 7. The elbow angle decreased after the takeoff, reaching its minimum value (about 60^{0}) priot to or approximately at the instant of maximum horizontal abduction, and then increased until the instant of ball contact. All subjects showed the maximum elbow angle at the instant of ball contact. Subject 7 did not vary the elbow angle very much during the arm swing phase, maintaining the angle at approximately 100^{o}.

For a detailed description of kinematics of striking arm during the spike, means and standard deviations of the three shoulder angles and the elbow angle were calculated at the instants of three events of

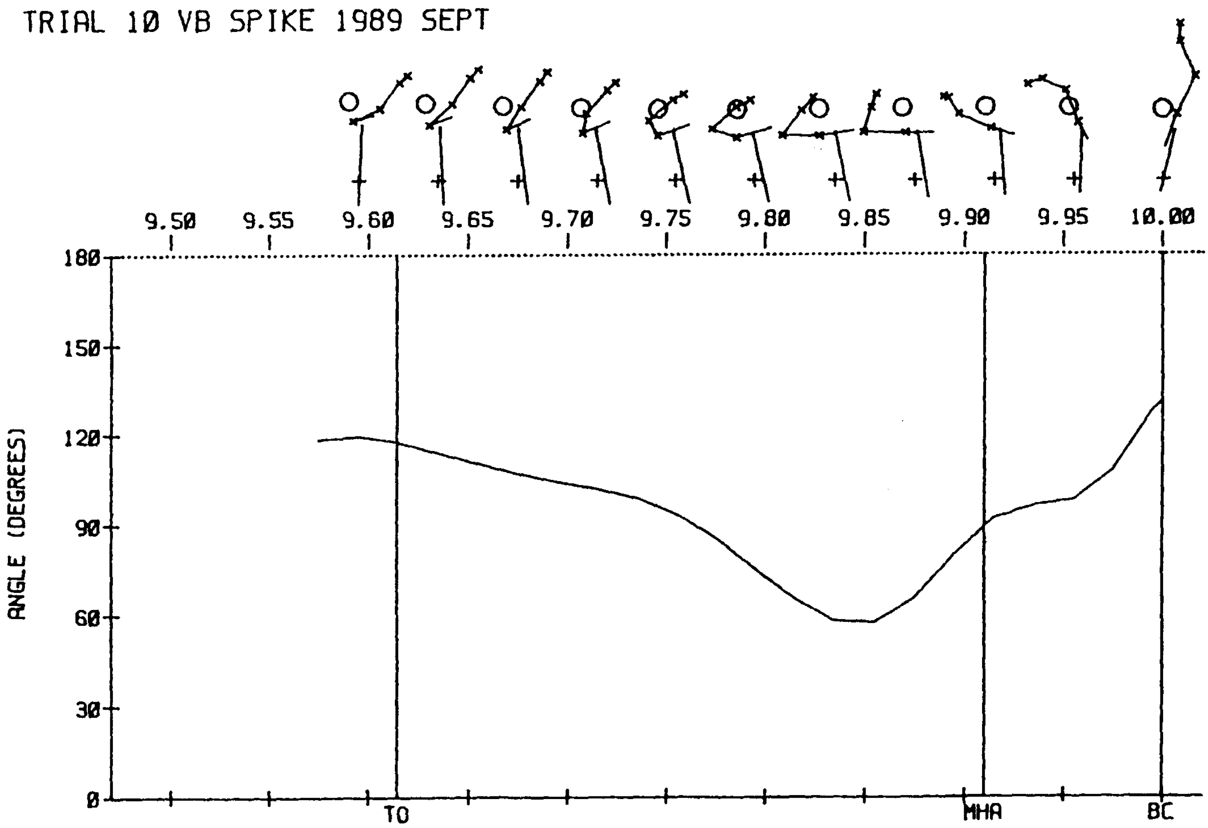

Figure 5. Angular posititition at the elbow.

the temporal periods. At the instant of takeoff, the internal-external rotation angle was $50 \pm 25^\circ$, the elevation angle was $21 \pm 10^\circ$ and the horizontal abduction-adduction was $69 \pm 23^\circ$, and the elbow angle was $120 \pm 16^\circ$. At the instant of maximum horizontal abduction, the internal-external rotation angle was $-12 \pm 47^\circ$, the elevation angle was $19 \pm 17^\circ$ and the horizontal abduction-adduction angle was $-7 \pm 14^\circ$, and the elbow angle was $80 \pm 15^\circ$. At the instant of ball contact, the internal-external rotation angle was $-55 \pm 24^\circ$, the elevation angle was $41 \pm 14^\circ$ and the horizontal abduction-adduction angle was $25 \pm 7^\circ$, and the elbow angle was $122 \pm 10^\circ$.

Figures 6 and 7 show the plots of the angular velocities of the three shoulder angles and the elbow angle, respectively. In Figures 6 and 7, it can be seen that horizontal abduction and external rotation at the shoulder and the elbow flexion dominated the backswing phase, and elevation and horizontal adduction at the shoulder and the elbow extension dominated the forward swing phase. The results of angular kinematics imply that the backswing style of the subjects in the present study was different from the correspondent in the study by Chung (1988), but similar to the correspondent in the study by Oka et al. (1975).

Speed of the hand, and the contributing factors

The speed of the hand (SPD_{HD}) and the contributions made by the velocity of the c.m. of the body (CON_G), the velocity of the c.m of the trunk relative to the c.m. of the body ($CON_{TK/G}$), the trunk rotation (CON_{TK}), the rotations at the shoulder (CON_{SH}), the elbow (CON_{ELB}) and the wrist (CON_{WR}), and the non-rigidity of body segments and inaccurate digitizing (CON_{ERR}) are shown in Figure 8. The patterns of the speed of the hand during the arm swing phase were similar for all subjects : The speed of the hand first decreased, then increased gradually, decreased again, reached a minimum value approximately at the instant of maximum horizontal abduction at the shoulder, and finally increased again very sharply, reaching its maximum value at the instant of ball contact. The patterns of the contributions of various components to the speed of the hand during

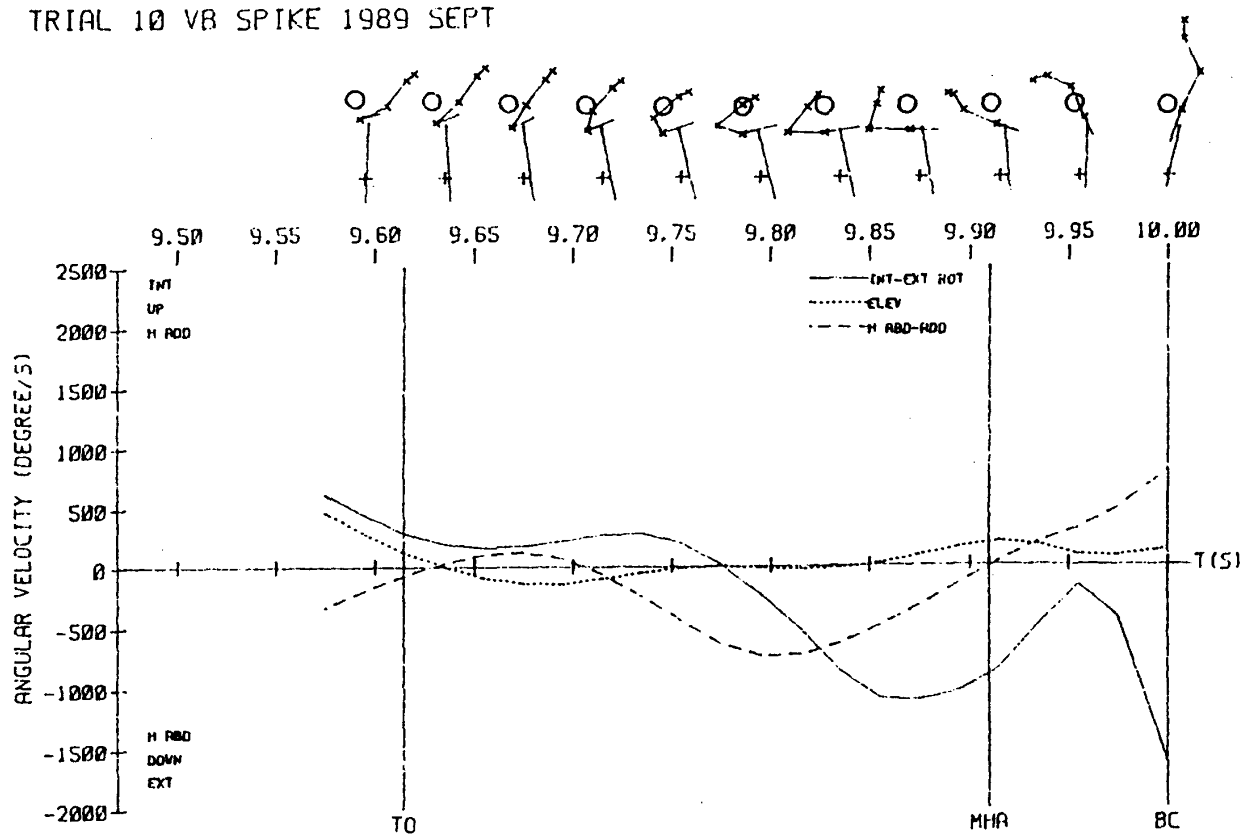

Figure 6. Angular velocity at the shoulder.

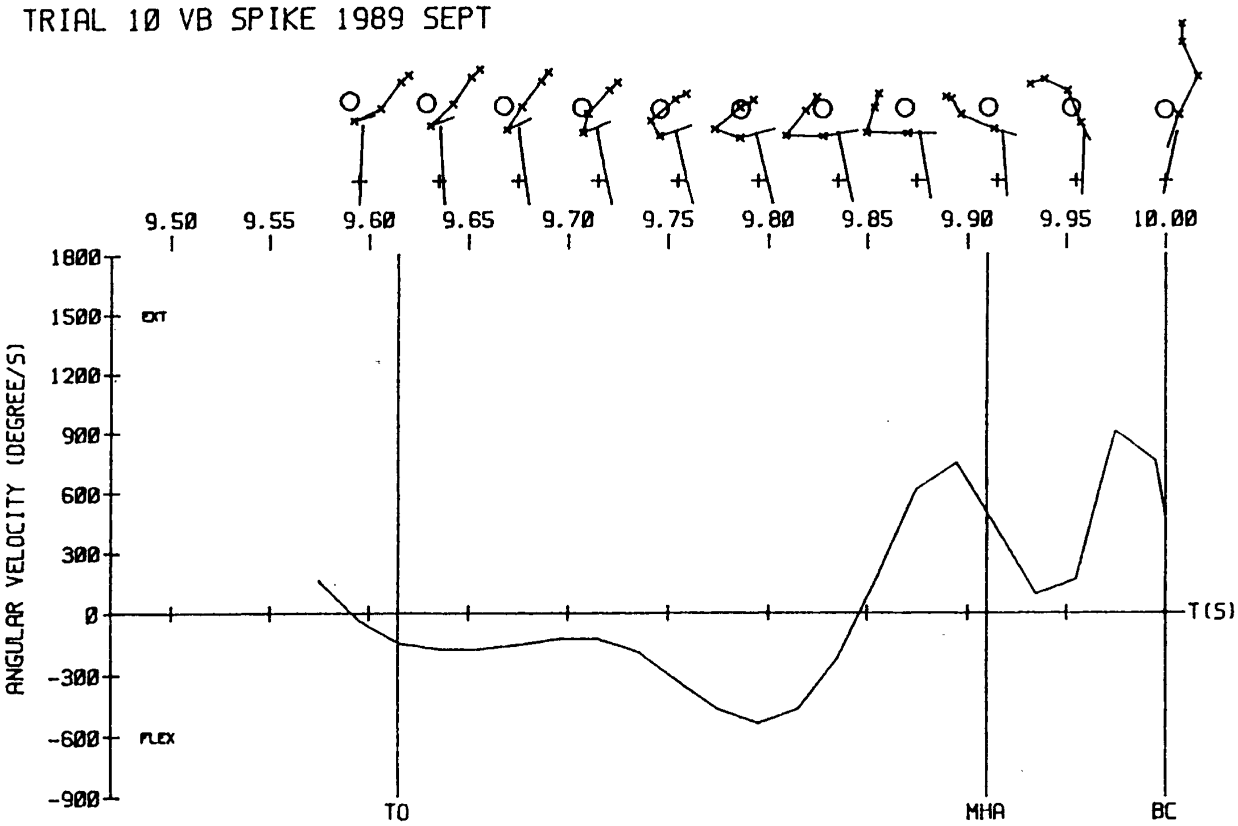

Figure 7. Angular velocity at the elbow.

the forward swing phase were different among the subjects, but for all subjects CON_G, CON_{TK}, CON_{SH}, and CON_{ELB} were the major contributors to the speed of the hand. Table 4 shows the contribution of each factor at the instant of ball contact, in a percentage to the speed of the hand (negative values indicate negative contributions to the speed of the hand). The data imply that CON_G, CON_{TK}, CON_{SH} and CON_{ELB} were also the major contributors to the speed of the hand.

The contribution made by the rotation of the trunk was further broken down into the contributions made by the twist (TW), forward somersault (F.SOM) and lateral somersault (L.SOM) rotations of the trunk, and the contribution made by the rotation at the shoulder was broken down into the contributions made by the somersault (SOM) and twist (internal-external) rotations of the upper arm at the shoulder with respect to the trunk (a "twist" is a rotation about the longitudinal axis of the segment ; a "somersault", a rotation about the transverse axis of the segment). The contributions to the speed of the hand by the various components of the trunk and shoulder and by the rotation at the elbow are shown in Figure 9. Table 5 shows the percentage contributions to the speed of the hand made by the various components of the trunk and shoulder rotations at the instant of ball contact.

The data in Figure 9 and Table 5 indicate that the speed of hand at the instant of ball contact was contributed mainly by the descending order of the somersault rotation at the shoulder, the twisting of the trunk, the elbow extension, the velocity of the center of mass of the body, and the forward rotation of the trunk. The results concerning the contribution to the speed of the hand are different from the corresponding data of previous study (Chung, 1988). In the latter (Chung, 1988), the speed of the hand was contributed by the order of the elbow extension (46 ± 17 %), the internal rotation at the shoulder (13.5 ± 16.5 %), the forward somersault of the trunk (10.5 ± 10.5 %), the somersault rotation at the shoulder (9.5 ± 11.0 %), and the velocity of the c.m. of the whole body ($7. \pm 4.0$ %).

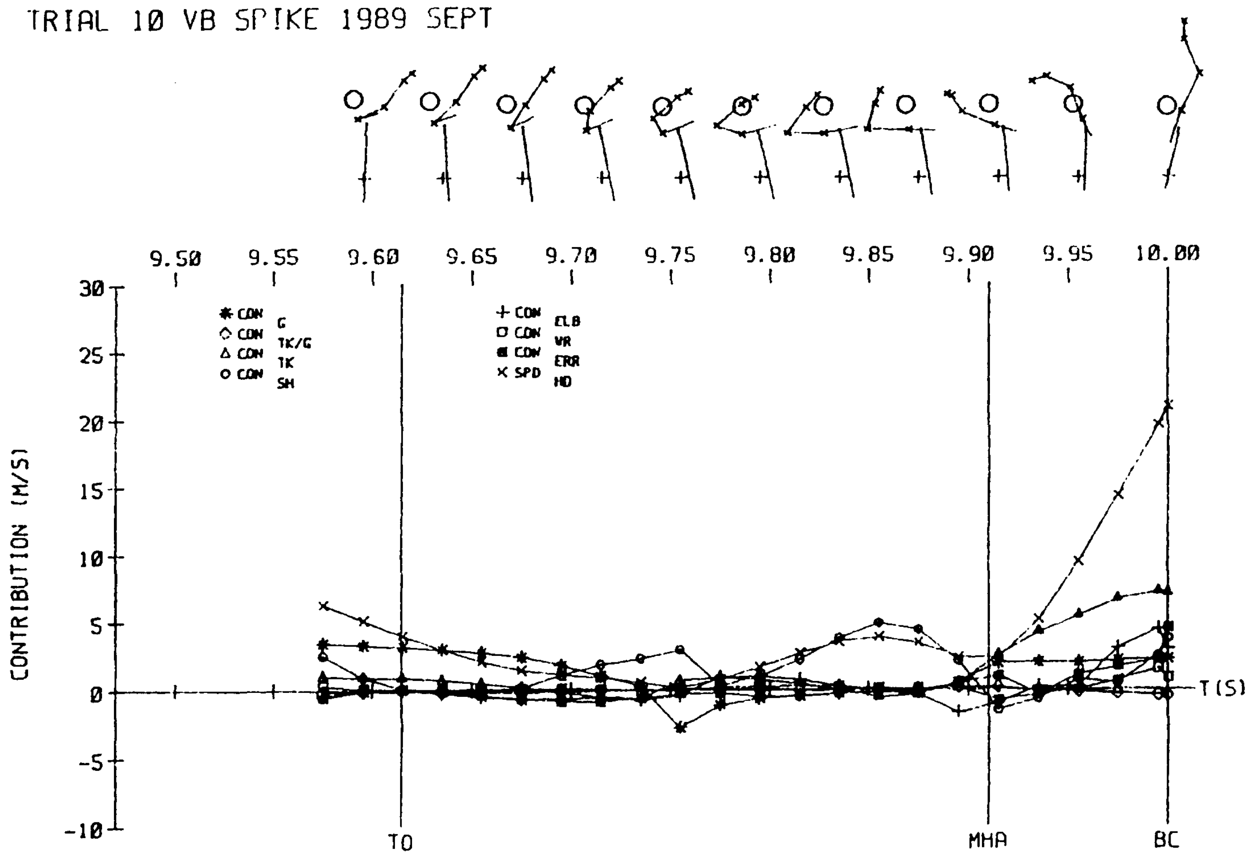

Figure 8. Contribution to the speed of the hand.

Table 4. Contributions to the speed of the hand at the instant of ball contact.

Subject	CONG	$CON_{TK/G}$	CON_{TK}	CON_{SH}	CON_{ELB}	CON_{WR}	CON_{ERR}
1	14.6	−2.6	21.8	22.4	15.3	1.9	26.7
2	14.2	−3.2	27.4	15.2	19.3	8.6	18.7
3	10.7	−2.3	34.0	17.9	14.1	3.8	21.7
4	9.6	−3.2	20.8	28.2	15.8	1.9	26.8
5	10.9	−2.7	23.0	29.0	9.9	6.7	23.2
6	5.7	−4.1	44.4	9.7	27.1	−0.5	17.7
7	11.7	−3.5	29.2	11.4	5.4	2.7	43.0
Mean	11.1	−3.1	28.7	19.1	15.3	3.6	25.4
S.D.	3.0	0.6	8.4	7.7	6.9	3.1	8.5

All values are in %, and have been rounded off to the nearest 0.1 %.

In order to further examine the diverse techniques of the arm swing used by the subjects, and to investigate whether they fall into various groups, a comparison was made between the contributions made by the twist rotation at the shoulder and the sum of the contributions made by the somersault rotation at the shoulder and the rotation at the elbow (which is also a somersault rotation). Figure 10 shows the sum of the contributions made by the somersault rotation at the shoulder and by the rotation at the elbow, plotted against the contribution made by the twist rotation at the shoulder. The plot shows that all subjects showed greater contribution by the sum of the contributions made by the somersault rotation at the shoulder and by the rotation at the elbow than by the twist rotation at the shoulder. It implies that all subjects used an in-plane arm swing technique just before impact, based primarily on the somersault rotation at the shoulder and extension at the elbow. In other words, the speed of the hand at impact was determined mainly by elevation and horizontal adduction at the shoulder and extention at the elbow.

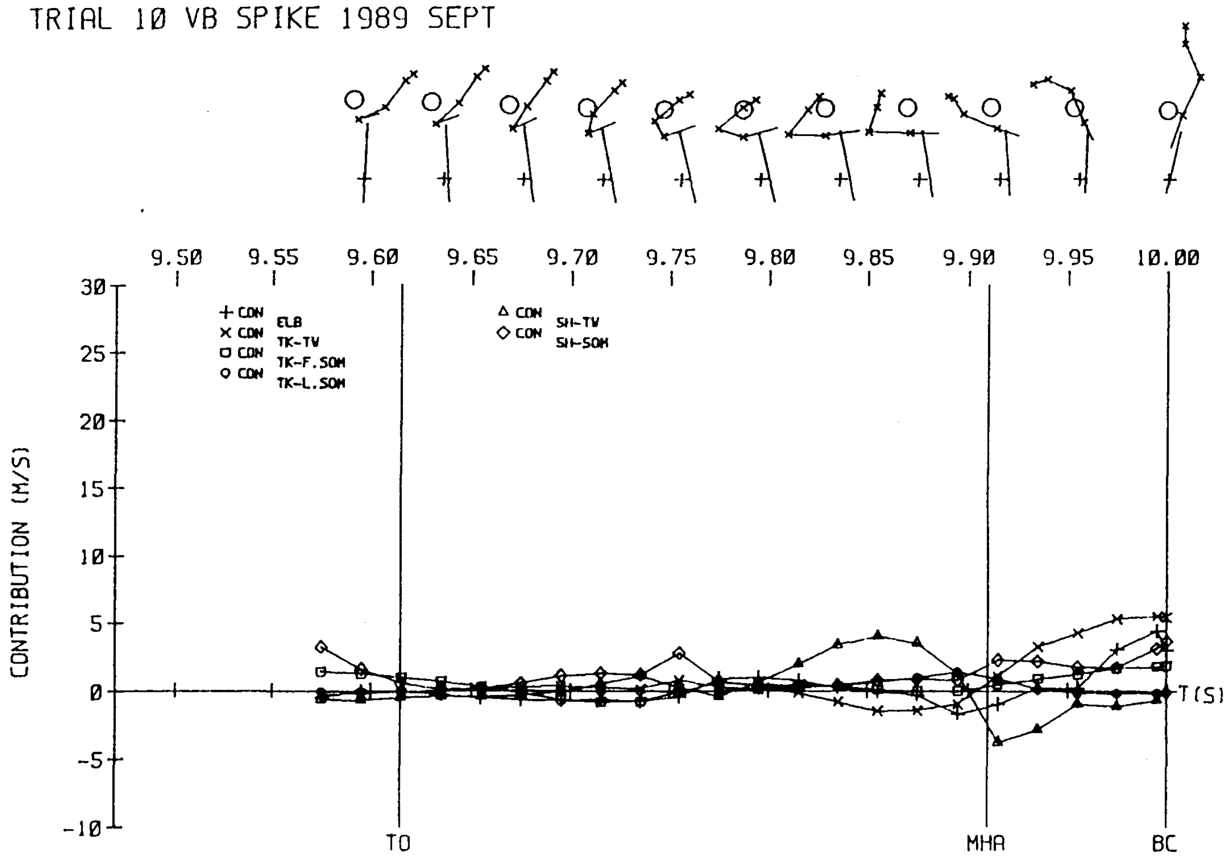

Figure 9. Contributions made by the Rotation at the elbow and the Rotion Components of the Trunk and the shoulder to the speed of the hand.

Table 5. Detailed contributions of the rotations of the trunk and of the shoulder to the speed of the hand at the instant of ball contact.

Subject	Trunk			Shoulder	
	TW	F.SOM	L. SOM	TW	SOM
1	9.9	12.0	−0.1	−0.3	22.7
2	19.9	8.5	−1.0	−7.2	22.4
3	25.9	8.8	−0.7	0.3	17.6
4	8.1	12.8	−0.1	−1.5	29.8
5	14.2	8.9	−0.1	−0.8	29.7
6	32.8	10.9	0.7	−1.6	11.3
7	20.7	10.4	−1.8	−0.9	14.3
Mean	18.8	10.3	−0.4	−1.7	21.1
S.D.	8.8	1.7	0.8	2.5	7.2

All values are in %, and have been rounded off to the nearest 0.1 %.

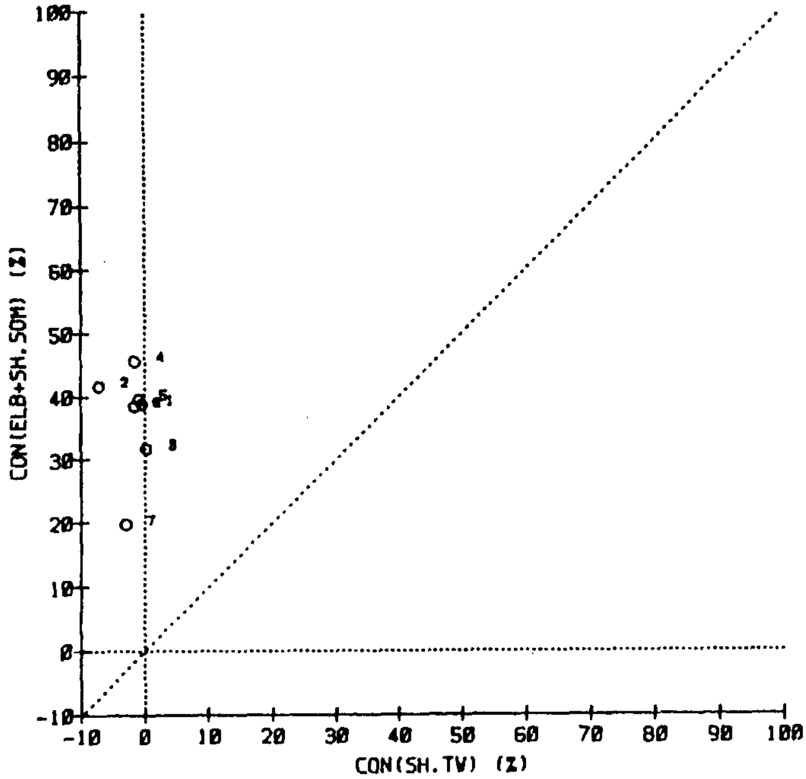

Figure 10. Relationship between the sum of contributions made by the somersault rotation at the shoulder and the rotation at the elbow, and contribution made by the twisting rotation at the shoulder.

To analyze the relationships between the motions of the shoulder and of the elbow, the contributions made by the rotation at the elbow at the instant of ball contact were plotted against those made by the somersault rotation at the shoulder (Figure 11). The graph helps to examine the extent to which the subjects used a "whip-like motion" technique, whereby decreasing or stopping the motion of a proximal segment could enhance the motion of the distal segment attached to it. Only subject 6 showed less contribution by the somersault rotation at the shoulder than by the rotation at the elbow at the instant of ball contact, which indicated that he used a "whip-like motion" technique. In other subjects, the speed of the hand at impact was due mainly to the somersault rotation at the shoulder with less degree of contribution by the elbow extension.

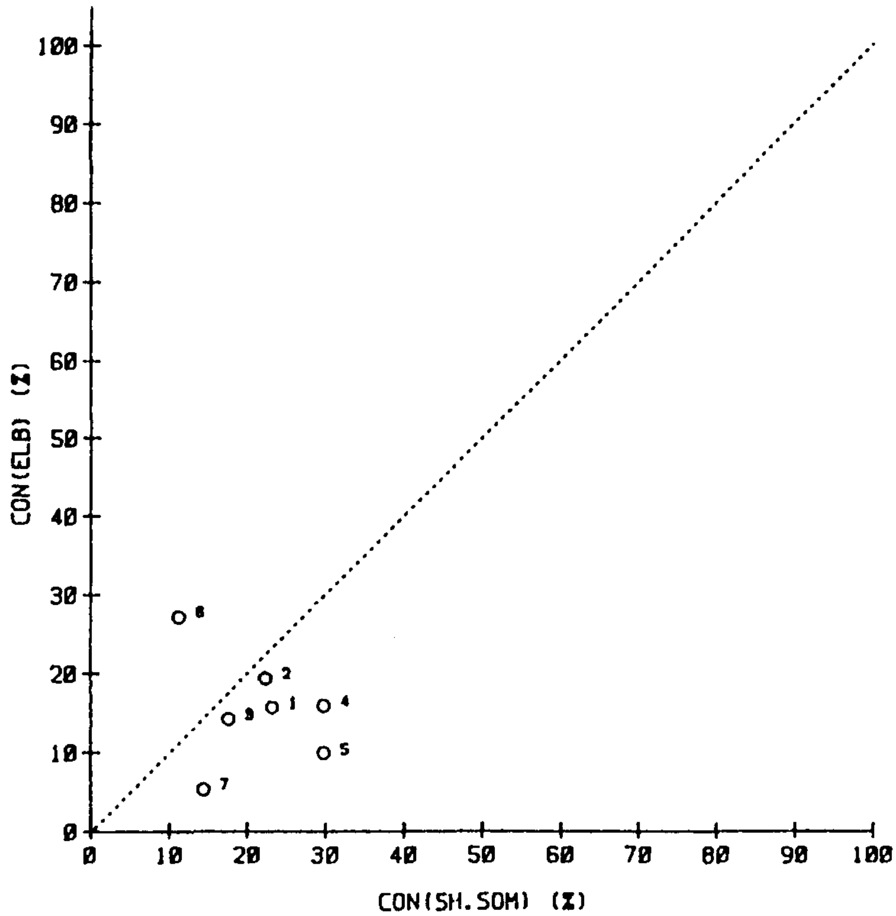

Figure 11. Relationship between contributions made by the somersault rotations at the shoulder and at the elbow.

The results of the contribution factors to the speed of the hand suggested that the subjects in the present study used a striking technique which was dominated by the trunk rotation and the somersault rotation at the shoulder. This striking technique uses mainly large proximal muscles rather than samll distal muscles, emphasizing the power of the motion rather than the accuracy of the motion. The reason that the subjects used this technique could have been to exert a large force on the ball during the impact period.

Other kinematic data

Table 6. Various kinematic parameters.

Subject	V_{HTO} (m/s)	V_{ZTO} (m/s)	θ (o)	h_{TO} (m)	h_{PK} (m)	h_{BC} (m)	t_{PK} (s)	Y_{ZBALL} (m)
1	3.06	3.05	45	1.32	1.80	1.79	9.971	0.009
2	2.42	3.14	52	1.32	1.82	1.82	9.995	0.119
3	2.27	3.06	53	1.34	1.82	1.79	9.926	0.083
4	2.30	3.43	56	1.28	1.89	1.87	9.950	0.106
5	2.53	3.39	53	1.25	1.84	1.83	9.975	0.053
6	1.84	3.53	62	1.33	1.97	1.90	9.882	0.045
7	2.24	3.12	54	1.31	1.81	1.80	9.971	0.047
Mean	2.38	3.25	54	1.31	1.85	1.83	9.953	0.066
S.D.	0.37	0.20	5	0.03	0.06	0.04	0.038	0.039

Table 6 shows the values of various kinematic parameters. The horizontal (V_{HTO}) and vertical (V_{ZTO}) velocity components of the c.m. of the body at the instant of takeoff were 1.4 ± 0.6 m/s and 2.7 ± 0.2 m/s, respectively, and the angle of inclination (θ) of the resultant velocity vector with respect to the horizontal plane at takeoff was $64 \pm 10°$. The height of the c.m. of the body at the instant of takeoff (h_{to}) was 1.21 ± 0.05 m (68.5 ± 0.5 % of the standing height of each subject). The maximum height reached by the c.m. of the body (h_{PK})

was 1.60±0.05 m. All subjects reached their maximum heights slightly before ball contact (t = 9.940±0.030 s), and therefore their c.m. was somewhat lower at the instant of ball contact than at the peak (h_{BC} = 1.57±0.05 m, about 0.02 m lower than at the peak of the jump).

The value of Y_{2BALL} indicated the Y_2 coordinate of the center of the ball relative to the shoulder at ball contact (positive values of Y_{2BALL} indicated ball positions to the left of the shoulder; negative values, ball positions to the right of the shoulder). Although there was a considerable amount of variability among the subjects, for all subjects the ball was located between the shoulder and the head at the ball contact (Y_{2BALL} = 0.066±0.039 m).

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