©Journal of Sports Science and Medicine (2003) **2,** 36-46
http://www.jssm.org

Research article

KINEMATIC ANALYSIS OF JAVELIN THROW PERFORMED BY WHEELCHAIR ATHLETES OF DIFFERENT FUNCTIONAL CLASSES

John W. Chow[1] ✉, Ann F. Kuenster [2] and Young-tae Lim [3]

[1]Department of Exercise and Sport Sciences, University of Florida, Gainesville, USA
[2]Department of Kinesiology, University of Illinois at Urbana-Champaign, USA
[3]Division of Sport Science, Konkuk University, Chungju, Korea

Received: 10 December 2002 / Accepted: 07 February 2003 / Published (online): 01 June 2003

ABSTRACT

The purpose of this study was to identify those kinematic characteristics that are most closely related to the functional classification of a wheelchair athlete and measured distance of a javelin throw. Two S-VHS camcorders (60 field· s^{-1}) were used to record the performance of 15 males of different classes. Each subject performed 6 - 10 throws and the best two legal throws from each subject were selected for analysis. Three-dimensional kinematics of the javelin and upper body segments at the instant of release and during the throw (delivery) were determined. The selection of kinematic parameters that were analyzed in this study was based on a javelin throw model showing the factors that determine the measured distance of a throw. The average of two throws for each subject was used to compute Spearman rank correlation coefficients between selected parameters and measured distance, and between selected parameters and the functional classification. The speeds and angles of the javelin at release, ranged from 9.1 to 14.7 m· s^{-1} and 29.6 to 35.8°, respectively, were smaller than those exhibited by elite male able-bodied throwers. As expected, the speed of the javelin at release was significantly correlated to both the classification (p<0.01) and measured distance (p<0.001). Of the segmental kinematic parameters, significant correlations were found between the trunk inclination at release and classification and between the angular speed at release and measured distance (p<0.01 for both). The angular speed of the shoulder girdle at release and the average angular speeds of the shoulder girdle during the delivery were significantly correlated to both the classification and measured distance (p<0.05). The results indicate that shoulder girdle movement during the delivery is an important determinant of classification and measured distance.

KEY WORDS: Biomechanics, disability, athletics, field events.

INTRODUCTION

Since 1960 when an Olympic style games for athletes with disabilities were organized for the first time in Rome, the opportunities of sports competition for wheelchair athletes have increased dramatically (DePauw and Gavron, 1995). The track and field are official events of the Paralympic Games and draw the largest number of athletes and spectators. Although the biomechanics of racing wheelchair propulsion have been investigated in many studies (e.g. Cooper, 1990; Chow et al., 2000b and 2001; Goosey et al., 1997; Mâsse et al., 1992; Van der Wonde et al., 1988; Wang et al., 1995), very few studies have focused on the movement characteristics of wheelchair field events such as shot put, discus, and javelin throws. Chow and Mindock (1999) studied the kinematics of discus throws performed by wheelchair athletes and concluded that the shoulder girdle movement during the forward swing is an important determinant of functional classification and measured distance. Chow et al. (2000a) attempted to identify those kinematic characteristics that are most closely related to the athlete's functional classification and measured distance of a shot put. They found the

Table 1. Subjects information and throws analyzed.

Subject ID	Classification	Mass (kg)	Age (yrs)	Skill* Level	Personal Best (m)	Throws Analyzed (m) #1	#2
1	F2	100.0	31	Elite	14.50	12.81	11.15
2	F2	72.7	25	Elite	10.16	8.77	8.85
3	F3	95.5	33	Elite	14.70	13.55	13.57
4	F4	77.3	47	Emerging	22.00	11.96	13.88
5	F4	77.5	37	Elite	21.78	17.70	17.80
6	F5	134.1	51	Elite	25.42	21.78	22.26
7	F5	127.3	20	Emerging	—	11.37	10.10
8	F5	107.7	48	Elite	27.50	21.86	24.06
9	F5	97.7	46	Elite	23.00	18.09	19.89
10	F5	111.4	26	Emerging	17.00	20.15	19.31
11	F6	127.3	20	Emerging	18.56	18.51	17.65
12	F7	88.6	30	Emerging	22.24	19.00	20.14
13	F7	105.9	48	Elite	30.01	27.10	26.44
14	F7	74.1	44	Elite	17.00	16.82	16.62
15	F8	79.5	19	Emerging	—	22.74	22.41

* Skill level rated by the Wheelchair Sports, USA.

height of the shot at release, the angular speed of the upper arm at release, the range of motion of the shoulder girdle during the delivery, and the average angular speeds of the trunk, shoulder girdle, and upper arm during the forward thrust (delivery) to be significantly correlated to both the classification and measured distance.

Competitors in wheelchair athletics are classified based on the neurological level of injury and the control and strength of different muscle groups (Wheelchair Sports, USA, 2002; see Appendix). For the field events, there are nine different functional classes, F1-F9. However, the javelin throw is not held for F1 class. Except for F8 and F9 athletes who are allowed to throw from a standing position and use an 800g javelin, wheelchair athletes in the other classes use a 600g javelin and perform throws from custom-made chairs that are pegged to the throwing circle by cables. Most athletes design their chairs and adopt sitting positions that suit their muscle function and strength, flexibility and personal preference. For able-bodied athletes, the javelin throw primarily consists of two parts -- the approach run and the delivery (also called the final thrust or launch phase). The approach run plays a key role in increasing the speed of release of the javelin, which is an important factor in determining the throw distance. However, all wheelchair athletes except F8 and F9 athletes have a little or no use of their lower extremities so they must concentrate on the delivery with their upper body. The variations in throwing techniques used by wheelchair athletes are likely attributed to the differences in disability, chair design, and sitting position. To explore the differences in technique among athletes of different level of disability, it was the purpose of this study to evaluate the relationships between selected kinematic parameters of the javelin throw performed by skilled wheelchair athletes and functional classification and measured distance. Based on the findings of Chow and Mindock (1999) and Chow et al. (2000a), it was hypothesized that shoulder girdle and trunk motions were significantly related to both the functional classification and measured distance.

METHODS

Fifteen male participants of a training camp for elite and emerging wheelchair field athletes organized by Wheelchair Sports, USA volunteered for this study (Table 1). They all signed informed consent documents before attending the camp. Nine of the participants had represented the United States at a Paralympic Games when the data were collected. All but two participants were right-handed. The data for the left-handed subjects were transposed and were treated as right-handers.

Theoretical considerations

The competition rules require that at least one part of the upper leg or buttock must be remained in contact with the seat cushion throughout the throwing action. Thus, hip motion is minimal even for those who have partial functions in the lower extremities. For the purpose of analysis, five linked segments can be identified between the hips and the javelin (Figure 1): the trunk (from mid-hips to mid-shoulders), the shoulder girdle (from mid-shoulders to throwing shoulder), the upper arm (from shoulder to elbow), the forearm (from elbow to wrist), and the hand (from wrist to third knuckle of hand). The kinematic characteristics of the javelin at release are determined by the angular kinematics of these five segments (Figure 2). Although some subjects moved their trunks back and forth several times prior to the delivery, this study focused on the kinematic characteristics of the throwing action and the release of the javelin.

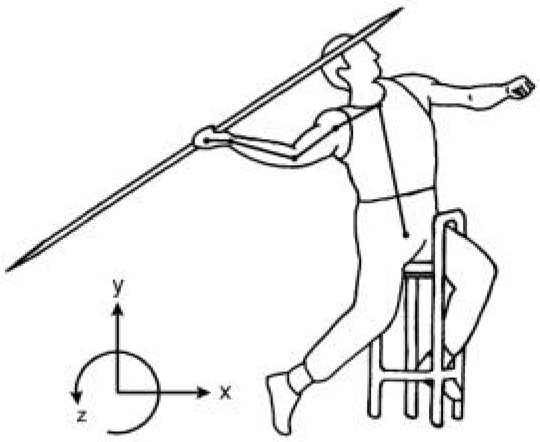


Figure 1. The chair used by an athlete must be located inside the circle but the footrest (s) or part of the legs can be protruded outside the circle. The segmental model used in this study is defined by the mid-hips, mid-shoulders, right shoulder, right elbow, right wrist, and third knuckle of the right hand.

The selection of kinematic parameters that were analyzed in this study was based on a javelin throw model showing the factors that determine the measured distance of a throw. In the second level of the model, a thrower will gain distance if the center of gravity of the javelin is located in front of the throwing circle at release and behind the tip of the javelin at landing. In the third level, the flight distance is determined by factors governing the trajectory of a projectile. The height of release is determined in part by the height of the chair, physique of the thrower, and body position at the instant of javelin release. For the rest of the model, consider the angular motion of a body segment, the velocity of the distal end-point of the segment (v_d) is determined by the velocity of the proximal end-point of the segment (v_p), the angular velocity of the segment (w), and the relative-position vector drawn from the proximal to distal end-points ($\boldsymbol{r}_{d/p}$):

$$v_d = v_p + \boldsymbol{w} \times r_{d/p} \quad (1)$$

During the delivery before the javelin is released, the average angular acceleration of a segment ($\bar{a}$) is given by:

$$\bar{a} = (\boldsymbol{w}_R - \boldsymbol{w}_B)/t \quad (2)$$

where $\boldsymbol{w}_B$ and $\boldsymbol{w}_R$ are the angular velocities of the segment at the beginning of the delivery and at release, respectively, and t is the time taken to complete the delivery. The average angular speed of a segment during the delivery ($\bar{s}$) is determined using the angular distance the segment traveled during the delivery (f) and the duration of the delivery:

$$\bar{s} = f / t \quad (3)$$

The part of the model below the third level is formed by repeated applications of equations 1-3. For example, in the fourth level of the model, the velocity of the wrist (the distal end-point of the forearm) at release is determined by the forearm length, the velocity of the elbow (the proximal end-point of the forearm) and the angular velocity of the forearm at release (equation 1). Applying the repeated block to the dotted lines below the box for the angular velocity of the forearm at release (5th level in Figure 2), the angular velocity of the forearm at release is determined by the angular velocity of the forearm at the beginning of the delivery, average angular acceleration of the forearm during the delivery, and the duration of the delivery (equation 2). The duration of the delivery is determined by the average angular speed of the forearm during the delivery and the range of motion of the forearm during the delivery (equation 3).

Assuming that the angular velocities of the different segments at the beginning of the delivery are zero, the average angular acceleration of each segment during the delivery is directly proportional to its angular velocity at release (equation 2). The terminal factors (boxes at the ends of the various paths) of the model examined in this study can be categorized into three groups: 1) the kinematic characteristics of the javelin at the instant of release, 2) the characteristics of different upper body segments at the instant of release, and 3) the kinematic characteristics of different segments during the delivery.

Data collection

Two S-VHS video camcorders (Panasonic AG-455, 60 field.s^{-1}) were used to record the throws. One camera was placed 10 m to the rear of the throwing circle (rear view) and the other was placed 18 m to the right-hand side of the circle (side view). The angle between the optical axes of the two cameras was approximately 90°. Data were collected in two sessions. Each subject performed 10 trials with a 2-

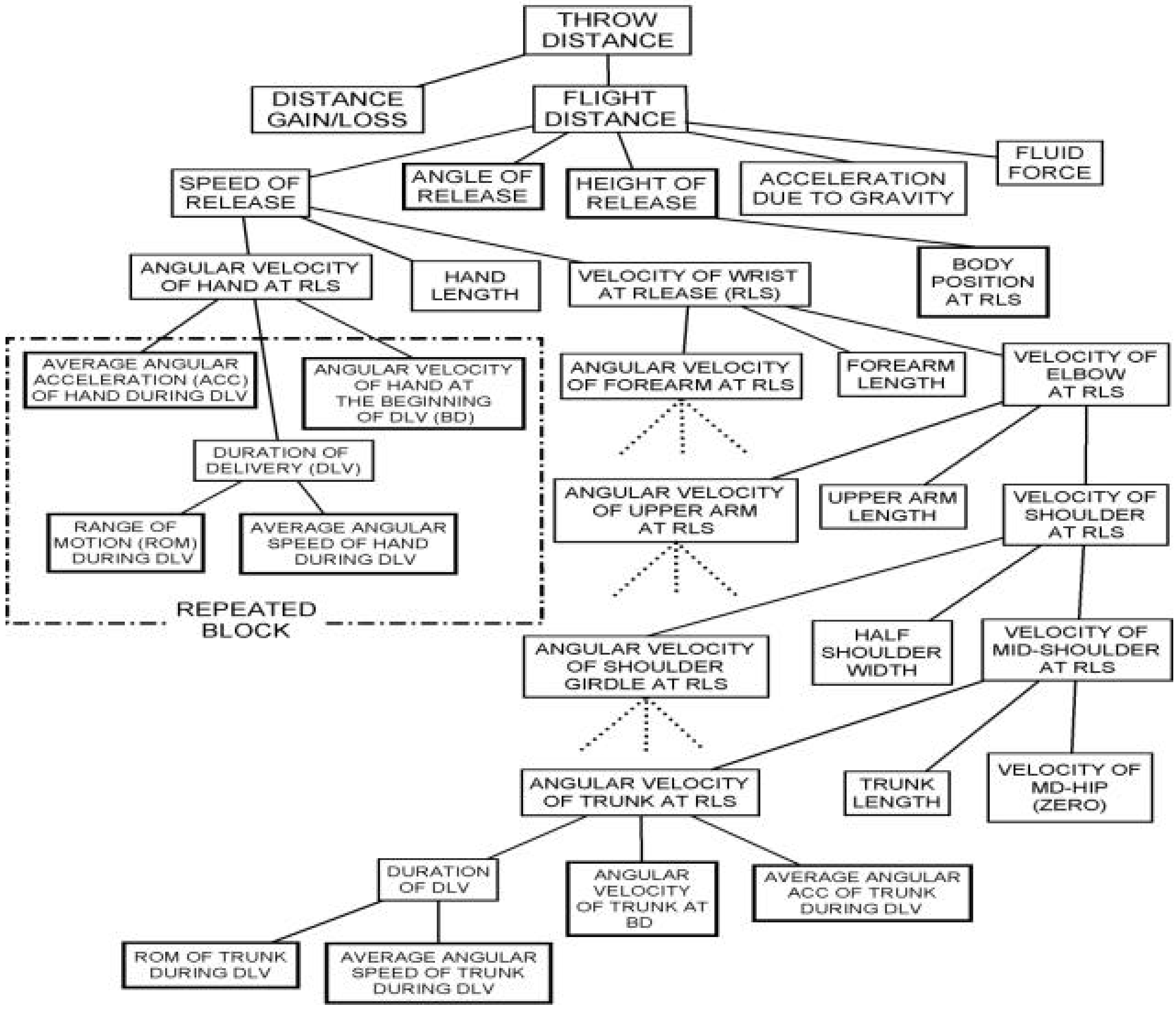


Figure 2. Factors that determine the measured distance of a javelin throw. The repeated block applies to the dotted lines below different upper body segments.

3 min rest between throws. A control object (Peak Performance Technologies, 25 control points, 2.1 × 1.9 × 1.6 m^3), a plumb-line and four markers were video-recorded before and after a data collection session for spatial reference and defining a global reference frame, respectively.

Data reduction

A Peak Motion Measurement System (Peak Performance Technologies) was used to manually extract two-dimensional coordinates from the video recordings. The direct linear transformation (DLT) procedure (Abdel-Aziz and Karara, 1971) was used to obtain 3-dimensional data on the performances of the throwers. The calibration errors (i.e., the root-mean-square error between the computed locations of the control points and their known locations) for the two data collection sessions were 6.70 and 6.19 mm, respectively.

The best two legal trials for each subject were selected for subsequent analysis. For each selected trial, the video recordings were digitized starting five fields before the beginning of the delivery and ending five fields after the javelin was released. Coordinates of 13 body landmarks (vertex, chin-neck intersect, suprasternal notch, left and right shoulders, elbows, wrists, third knuckles, and hips), middle of the front edge of the seat, and ends and center of the cord grip on the javelin were obtained from each field. Because the two cameras were not synchronized electronically, the instant of release (defined as the first field in which the thrower lost contact with the javelin) was used for synchronization purposes. The raw 3-dimensional data were smoothed using a second-order, low-pass, recursive digital filter with cut-off frequency of 7.4 Hz (Yu, 1988). Coordinate transformation was performed so that the x-axis was horizontal and pointing toward the front (throw direction) and the z-axis was horizontal and pointing to the right of the throwing circle. The y-axis was pointing vertically upward (Figure 1), that is, the x-y plane was parallel to a vertical plane that bisected the throwing sector.

The horizontal, vertical, and resultant velocities of the javelin at release were determined using the unfiltered coordinates of the grip center of the javelin at release and two fields after release, the known elapse time (1/30 s), and the equations for uniformly acceleration motion. The horizontal velocity is the component of the resultant velocity in the x-z plane. The angle of release was determined from the horizontal and vertical velocities at release. The inclination of a body segment was computed as the smallest angle between the longitudinal axis of the segment and the horizontal (x-z) plane. A positive inclination angle indicates that the distal end-point was located above the proximal end-point of the segment. For the trunk segment, the distal and proximal end-points are the mid-shoulders and mid-hips, respectively. The attitude angle was computed as the inclination of the javelin at release. The angle of attack was obtained by subtracting the angle of release from the attitude angle. The range of motion (ROM) of a segment during the delivery was obtained by summing the angles between the same segment in adjacent fields, computing using the dot product, from the beginning of the delivery to the instant of release. The angular speeds of different upper body segment were computed using the central difference technique (Wood, 1982). The average angular speed of a segment during the delivery was determined from ROM and the duration of the delivery (equation 3).

Data analysis

For each parameter, means and standard deviations were computed for each functional class. The average of two throws for each subject was used to compute Spearman rank correlation coefficients between selected parameters and measured distance, and between selected parameters and the functional classification. Correlation coefficients of $|r| \geq 0.51$, $|r| \geq 0.64$, and $|r| \geq 0.76$ were required to attain statistical significance at the 0.05, 0.01, and 0.001 levels of probability, respectively (n=15).

RESULTS

Kinematic characteristics of javelin at release

The throw distances performed by our subjects ranged from 8.77 to 27.10 m (Table 1). The average speeds of release and the average angles of release for different classes ranged from 9.1 to 14.7 $m \cdot s^{-1}$ and 29.6° to 35.8°, respectively (Table 2). Both positive and negative angles of attack were observed.

The grip center of the javelin was located behind the anterior edge of the seat for most subjects (Table 3). And in most trials, the grip center was located directly behind (or slightly off to the right) and above the right shoulders at the instant of release. The right shoulder was higher than, to the right of, and behind the left shoulder at the instant of release.

At the instant of release, the trunk was not in an upright position (Table 4). The inclination of the shoulder girdle indicated that the right shoulder was higher than the left shoulder at the instant of release. The difference in shoulder heights can be estimated from the results shown in Table 3. The difference in the inclinations of the forearm and upper arm at release indicates that the javelin was released before the arm was fully extended.

The average angular speeds at release for different classes ranged from: 1.52 to 2.16 $rad \cdot s^{-1}$ for the trunk; 1.41 to 7.78 $rad \cdot s^{-1}$ for the shoulder girdle; 2.90 to 13.37 $rad \cdot s^{-1}$ for the upper arm; 10.63 to

Table 2. Means (± standard deviations) for selected characteristics of the javelin at the instant of release.

	Classification						
	F2 (n=2)	**F3 (n=1)**	**F4 (n=2)**	**F5 (n=5)**	**F6 (n=1)**	**F7 (n=3)**	**F8 (n=1)**
Speed of release ($m \cdot s^{-1}$)							
Horizontal	7.7 (.7)	9.3 (1.0)	10.5 (1.0)	11.1 (1.9)	11.1 (.8)	12.3 (1.1)	12.5 (1.0)
Vertical	4.7 (.5)	6.6 (.0)	5.9 (1.3)	8.0 (1.8)	7.3 (.2)	7.6 (1.5)	7.7 (.8)
Resultant	9.1 (.9)	11.4 (.8)	12.1 (.4)	13.8 (2.2)	13.4 (.6)	14.4 (1.7)	14.7 (1.3)
Angle of release (°)	31.4 (1.6)	35.7 (2.6)	29.6 (7.4)	35.8 (5.2)	33.4 (3.0)	31.5 (3.2)	31.6 (.6)
Attitude Angle (°)	26.3 (1.3)	29.2 (.4)	37.6 (10.4)	37.9 (10.4)	32.6 (2.2)	35.0 (4.9)	36.8 (10.2)
Angle of Attack (°)	-5.2 (.8)	-6.5 (2.2)	8.0 (5.7)	2.1 (9.0)	-.8 (5.1)	3.5 (3.2)	5.2 (9.6)

A negative value indicates that the angle of release is smaller than the attitude angle.

Table 3. Means (± standard deviations) for the javelin location at the instant of release.

	Classification						
	F2 (n=2)	**F3 (n=1)**	**F4 (n=2)**	**F5 (n=5)**	**F6 (n=1)**	**F7 (n=3)**	**F8 (n=1)**
Height above ground (m)							
	1.72 (.08)	1.96 (.14)	2.02 (.13)	2.20 (.15)	2.12 (.04)	2.22 (.07)	2.05 (.08)
Forward location relative to seat front (m)							
	-.31 (.06)	.16 (.29)	-.20 (.32)	-.25 (.16)	-.27 (.18)	-.21 (.22)	-.07 (.16)
Location relative to right shoulder (m)							
Forward	15 (.02)	07 (.23)	.13 (.24)	.12 (.16)	.20 (.09)	.05 (.16)	.08 (.13)
Vertical	.59 (.03)	.56 (.15)	.86 (.17)	.87 (.16)	.78 (.04)	.78 (.12)	.58 (.08)
Lateral	.15 (.07)	.56 (.08)	.53 (.12)	.19 (.18)	.26 (.04)	.42 (.22)	.34 (.02)
Location relative to left shoulder (m)							
Forward	-.01 (.03)	.05 (.24)	.05 (.12)	.09 (.12)	.04 (.18)	.09 (.23)	.08 (.14)
Vertical	.70 (.07)	.76 (.14)	.87 (.07)	1.06 (.16)	.82 (.05)	.94 (.08)	.79 (.08)
Lateral	.48 (.05)	.92 (.10)	.50 (.29)	.51 (.18)	.65 (.03)	.55 (.14)	.68 (.02)

A positive value indicates that the cord center of the javelin was located in front of, above, or to the right of the reference location.

25.98 rad· s^{-1} for the forearm; and 6.14 to 30.87 rad· s^{-1} for the hand (Table 4). The range of angular speed increased as the segments became more distal. It is apparent that distal segments moved faster than proximal segments at the instant of release. The relatively large differences between the angular speeds of upper arm and forearm indicating a large elbow extension speed at the instant of release. Judging from the angular speeds of forearm and hand, wrist flexion actions at the instant of release are noticeable in subjects of higher classifications.

The range of average ROM during the delivery for different classes were 27.1 to 52.4º for the trunk, 59.7 to 128.6º for the shoulder girdle, 78.9 to 167.7º for the upper arm, 87.8 to 151.8º for the forearm, and 112.2 to 181.7º for the hand (Table 5). The hand ROM was the greatest in 86% of all trials and the trunk ROM was the smallest in all trials analyzed.

The range of average angular speeds during the delivery for different classes were 1.23 to 2.40 rad.s^{-1} for the trunk, 2.64 to 5.34 rad· s^{-1} for the shoulder girdle, 3.01 to 6.05 rad· s^{-1} for the upper arm, 3.24 to 6.56 rad· s^{-1} for the forearm, and 4.12 to 8.31 rad· s^{-1} for the hand (Table 5). It is worth noting that the values for the arms and hand found in F2 subjects are comparable to those exhibited by subjects in the other classes. However, the average angular speeds of the shoulder girdle for F2 subjects are smaller that the corresponding values found in the other subjects.

Table 4. Means (± standard deviations) for the body segment kinematics at the instant of release.

	Classification						
	F2 (n=2)	**F3 (n=1)**	**F4 (n=2)**	**F5 (n=5)**	**F6 (n=1)**	**F7 (n=3)**	**F8 (n=1)**
Segment inclination* (º)							
Trunk	61.6 (10.3)	63.6 (.7)	68.2 (4.5)	63.5 (7.7)	77.3 (2.4)	77.5 (6.5)	75.2 (3.0)
SG	18.8 (10.3)	30.0 (3.3)	.8 (18.4)	27.9 (10.4)	6.0 (1.1)	21.9 (17.0)	31.1 (.4)
UA	42.5 (5.6)	18.2 (.6)	16.8 (7.4)	52.2 (11.4)	39.8 (2.5)	34.5 (21.4)	47.4 (3.0)
Forearm	64.0 (1.6)	27.8 (1.3)	58.4 (15.5)	73.0 (9.7)	68.0 (10.2)	51.8 (34.0)	64.2 (10.2)
Hand	77.3 (6.9)	39.2 (10.7)	58.6 (18.9)	62.0 (17.0)	41.1 (3.5)	44.8 (22.9)	59.8 (9.0)
Angular speed (rad· s^{-1})							
Trunk	2.13 (1.07)	2.16 (.41)	1.56 (.61)	1.59 (.68)	1.52 (.14)	1.99 (.91)	2.15 (.03)
SG	5.01 (.59)	1.41 (.20)	3.52 (.46)	4.71 (1.66)	3.77 (.34)	7.78 (1.12)	7.62 (2.08)
UA	6.58 (1.54)	13.37 (1.62)	2.90 (2.31)	7.18 (1.65)	8.92 (1.81)	8.02 (5.41)	9.08 (1.58)
Forearm	14.95 (.79)	15.19 (1.19)	10.63(11.57)	23.20 (3.86)	23.10 (1.39)	18.20 (9.74)	25.98 (4.64)
Hand	6.14 (2.35)	14.88 (6.14)	14.94 (15.71)	30.87 (4.45)	26.67 (9.00)	25.63 (11.75)	29.39 (8.52)

* A positive value indicates that the distal endpoint was located above the proximal endpoint of the segment.
SG = Shoulder Girdle; UA = Upper Arm.

Table 5. Means (± standard deviations) for the body segment range of motion and average angular speed during the delivery.

	Classification						
	F2 (n=2)	**F3 (n=1)**	**F4 (n=2)**	**F5 (n=5)**	**F6 (n=1)**	**F7 (n=3)**	**F8 (n=1)**
Segment range of motion (°)							
Trunk	27.1 (7.3)	53.6 (13.3)	31.6 (2.6)	34.3 (19.1)	35.2 (3.3)	40.6 (7.9)	52.4 (3.2)
SG	59.7 (16.0)	128.6 (18.0)	73.6 (12.5)	100.4 (35.1)	76.0 (2.5)	124.0 (5.7)	117.2 (.6)
UA	128.6 (39.7)	125.8 (9.4)	78.9 (47.4)	126.4 (12.6)	167.7 (14.4)	141.4 (12.2)	131.1 (11.0)
Forearm	122.3 (24.7)	141.8 (13.0)	87.8 (65.8)	147.3 (29.6)	151.8 (30.2)	126.6 (46.4)	144.8 (30.4)
Hand	141.4 (57.2)	162.6 (47.2)	112.2 (86.5)	164.0 (39.8)	176.5 (40.0)	158.0 (46.2)	181.7 (20.2)
Average angular speed (rad· s^{-1})							
Trunk	1.26 (.66)	1.73 (.28)	1.33 (.22)	1.36 (.79)	1.23 (.12)	1.77 (.56)	2.40 (.29)
SG	2.64 (1.07)	4.25 (1.14)	3.22 (1.24)	3.95 (1.14)	2.65 (.09)	5.32 (1.08)	5.34 (.30)
UA	5.85 (2.70)	4.21 (1.39)	3.01 (1.29)	5.10 (.96)	5.85 (.50)	6.05 (1.25)	5.99 (.87)
Forearm	5.56 (2.45)	4.73 (1.49)	3.24 (1.86)	5.80 (.47)	5.29 (1.06)	5.13 (.97)	6.56 (.98)
Hand	6.14 (2.35)	5.21 (0.61)	4.12 (2.48)	6.45 (0.95)	6.16 (1.40)	6.47 (0.69)	8.31 (1.43)

SG= Shoulder Girdle; UA= Upper Arm.

Correlation coefficients

A significant positive correlation was found between classification and measured distance (r=0.66, p<0.05). The correlation coefficients between selected parameters and the classification, and between selected parameters and measured distance, are given in Table 6. The horizontal, vertical, and resultant velocities of the javelin at release were significantly correlated with both the classification and measured distance. The high correlation coefficients, ranging from r=0.57 (p<0.05) to r=0.95 (p<0.001), indicate that the speed of release is a major determinant of the variation in measured distance observed in this study and is highly correlated to the classification.

The height of release was significantly correlated with both the classification and measured distance (r=0.62 and r=0.60, respectively). One reason why athletes of a higher class had greater release height was because they could drop the left shoulder more and elevate the right shoulder more than athletes of a lower class.

The inclination of the trunk at release was significantly correlated with the classification (r=0.67, p<0.01) but not the measured distance. The angular speed of the shoulder girdle at release was significantly correlated with both the classification and measured distance (r≥0.61, p<0.05). The angular speed of the forearm at release was significantly correlated with the classification (r=0.55, p<0.05) but not the measured distance. The angular speed of the hand at release was significantly correlated with the measured distance (r=0.66, p<0.01) but not the classification.

Of the segmental ROM examined in this study, only the shoulder girdle ROM was significantly related to the classification (r=0.56, p<0.05). Of the segmental average angular speeds identified in the mechanical model shown in Figure 2, only the average angular speed of shoulder girdle yielded significant correlations with both the classification and the measured distance (r≥0.65, p<0.01). The only other significant correlation was between the average angular speed of hand and the measured distance (r=0.52, p<0.05).

DISCUSSION

Limitations

There are several possible sources of error in the kinematic measurements obtained in this study. In addition to possible errors resulting from manual digitizing and limited resolution of the video images, the cameras were not electronically synchronized. The error associated with the use of critical instants to synchronize two sets of video recordings is generally small (Yeadon, 1989) and should not affect the main findings. The correlation coefficients presented in Table 6 serve to provide an overview of inter-relationships among measured distance, classification and various variables. The significant correlations should be interpreted with caution because of the potential errors associated with multiple tests.

Kinematic characteristics

As expected, the speeds of release (Table 2) were smaller than those reported for javelin throws by male elite able-bodied athletes: 24.8 m· s^{-1} (Ikegami et al., 1981), 29.01 m· s^{-1} (Terauds, 1983), 26.7 m· s^{-1} (Miller and Munro, 1983), 27.36 m.s^{-1} (Komi and Mero, 1985), 29.4 m· s^{-1} (Rich et al., 1985), 29.6 m· s^{-1} (Whiting et al., 1991), 28.3 m· s^{-1} (Mero et al., 1994), and 27.0 m· s^{-1} (Bartlett et al., 1996). It is certain that a direct comparison between wheelchair

Table 6. Spearman rank order correlation coefficients.

Variables	Classification	Measured Distance
Javelin at release		
Horizontal velocity	0.74**	0.91***
Vertical velocity	0.57*	0.94***
Resultant velocity	0.71**	0.95***
Angle of Release	-0.09	0.19
Height of Release	0.62*	0.60*
Forward location relative to seat front	0.08	0.02
Location relative to right shoulder		
Forward	-0.13	-0.15
Vertical	0.23	0.20
Lateral	0.18	0.14
Location relative to left shoulder		
Forward	0.45	0.04
Vertical	0.36	0.41
Lateral	0.12	0.29
Body segment at release		
Inclination		
Trunk	0.67**	0.10
Shoulder Girdle	0.24	0.40
Upper Arm	0.18	0.30
Forearm	0.25	0.41
Hand	-0.33	-0.33
Angular speed		
Trunk	0.06	0.18
Shoulder Girdle	0.65**	0.61*
Upper Arm	0.27	0.44
Forearm	0.55*	0.44
Hand	0.34	0.66**
Range of motion during the forward swing		
Trunk	0.28	0.47
Shoulder Girdle	0.49	0.56*
Upper Arm	0.48	0.15
Forearm	0.24	0.09
Hand	0.22	0.19
Average angular speed during the forward swing		
Trunk	0.32	0.49
Shoulder Girdle	0.65**	0.67**
Upper Arm	0.41	0.15
Forearm	0.20	0.30
Hand	0.38	0.52*

Significant at * $p<0.05$, ** $p<0.01$, or *** $p<0.001$ level.

athletes and able-bodied athletes may not be appropriate because our subjects did not have approach run. For able-bodied throwers, the approach run is a critical factor to increase the speed of release. It is obvious that the advantages of using lighter javelins by wheelchair athletes are not enough to offset the disadvantages due to the lack of approach run in javelin throws. However, the angles of release were comparable to those performed by male elite able-bodied throwers: 32.9° (Ikegami et al., 1981), 31.7° (Terauds, 1983), 37.6° (Miller and Munro, 1983), 38° (Komi and Mero, 1985), 32.7°

(Rich et al., 1985), 36° (Whiting et al., 1991), 32° (Mero et al., 1994), and 37.1° (Bartlett et al., 1996). The attitude angles were similar to those found in male elite able-bodied throwers: 33° (Kunz, 1980), 36.7° (Terauds, 1983), 39.5° (Miller and Munro, 1983), 41° (Komi and Mero, 1985), 38.5° (Rich et al., 1985), 37° (Whiting et al., 1991), and 31° (Mero et al., 1994). The angles of attack were also comparable to those measured in male elite able-bodied throwers: 7.5° (Ikegami, et al., 1981), 6.2° (Terauds, 1983), 1.9° (Miller and Munro, 1983), 2° (Komi and Mero, 1985), 8.2° (Rich et al., 1985), 1° (Whiting et al., 1991), -1° (Mero et al., 1994), and 0.34° (Bartlett et al., 1996).

According to competition rules, the seat of an athlete's chair (including the cushion) for field events must not exceed 75 cm in height (Wheelchair Sports, USA, 2002). For wheelchair athletes, the chair design is important because it may help or hinder the performance depending on how well it fits the thrower's ability. As a result, athletes use chairs of different seat heights to optimize their performance. The heights of release found in F2 subjects (Table 3) were considerably lower than those found in male elite able-bodied javelin throwers: 2.01 m (Terauds, 1978), 2.05 m (Miller and Munro, 1983), 2.09 m (Rich et al., 1985), and 1.81 m (Mero et al., 1994). Although the height of release is relatively less important than the speed and the selected angles, if all else is equal, a thrower who has a higher sitting height and longer arms will have a higher release height and an advantage over throwers with lower release heights.

While most subjects in this study released the javelin behind the seat front (Table 3), wheelchair athletes usually release the discus and shot in front of the seat front (Chow and Mindock, 1999; Chow et al., 2000a). The right shoulder was located behind the left shoulder at the instant of release in most trials. To some wheelchair athletes, the lack of normal trunk movements prevents a complete axial rotation (twisting) of the trunk before the release. As a result, the right shoulder was located behind the left shoulder at the instant of release. Compared to the upright or forward lean body position at release found in able-bodied throwers, the trunk inclinations of our subjects indicate a backward leaning position, especially for throwers in lower classes, at the instant the javelin was released (Table 4). It seems that both a lack of control in trunk movement in some of our subjects and the sitting position adopted by wheelchair throwers may limit the trunk action during the delivery.

Because inclinations of the upper arm and forearm were positive at the instant of release, the sum of the inclination angles of these two segments can provide an estimate of the angle of elbow extension. The angular speed of elbow extension can also be estimated by summing the angular speeds of the upper arm and forearm because the elbow was extending at the instant of release. In general, the elbow extension angles at the instant of release found in this study (Table 4) were smaller than those exhibited by male elite able-bodied athletes: 127° (Komi and Mero, 1985), 123° (Mero et al., 1994), and 126° (Bartlett et al., 1996). The angular speeds of elbow extension at the instant of release were also considerably smaller than those found in male elite able-bodied javelin throwers: 41.63 $rad \cdot s^{-1}$ (Komi and Mero, 1985). When compared to able-bodied throwers, it is not clear whether the smaller elbow extension angles and angular speeds found in wheelchair throwers are due the differences in strength or technique, or a combination of both.

The greatest average angular speed was in the hand in 80% of the throws analyzed. This demonstrates that the hand motion is also a major factor for determining the outcome of a javelin throw performance. Although the contribution of hand segment is limited by its short segment length (equation 1), the effort to increase the hand speed should not be overlooked.

Correlation coefficients

The correlation coefficient found between the resultant velocity of release and measured distance (r=0.95, p<0.001) is very similar to the corresponding values found in male elite able-bodied athletes: r=0.93 to r=0.99 (Ikegami et al., 1981; Miller and Munro, 1983; Komi and Mero, 1985). Because the speed of release is determined by the motions of upper body segments during the delivery (Figure 2), the significant positive correlation between the speed of release and classification (r=0.71, p<0.01) suggests that, in general, the current classification system is reasonable in distinguishing the functional differences among wheelchair athletes. The significant correlations between speed and height of the javelin at release and the classification and measured distance indicate that the variation in these release parameters was primarily due to the functional capability of the athletes. The importance of achieving greater speed and height of release should be emphasized to improve the performance.

In general, the results support the hypothesis that shoulder girdle and trunk motions are significantly related to both the functional classification and measured distance. The significant correlation between the trunk inclination angle at release and the classification may suggest that athletes of lower classes do not have enough muscular strength in the lower trunk to move the trunk to a more upright position during the delivery.

In fact, several of our subjects had to grasp a vertical pole attached to the front of the chair for support throughout the delivery. The significant correlations between the angular speed of the shoulder girdle at release and average angular speed of the shoulder girdle during the delivery and the classification and measured distance imply that the shoulder girdle motions not only differentiate the functional differences among wheelchair athletes but also play a role in determining the variation in measured distance. The significant correlations between the angular speed of the hand at release and average angular speed of the hand during the delivery, and measured distance indicate that the hand movement during the delivery is also a major factor in determining javelin throw performance.

PRACTICAL IMPLICATIONS AND CONCLUSION

The ability of the torso to support effective arm and leg actions (the so-called core stability) is essential to performance and injury prevention in many sports. To provide a stable base for shoulder and arm motions, wheelchair javelin athletes should strive to maximize their functional potential in trunk movements. In addition, they should explore a chair design that allows a sitting position and technique for optimal control of trunk movements. Instead of leaning backward at the instant of release, athletes need to experiment different techniques so that they can have a more erected posture at the release of javelin. Within their functional capability, athletes in the lower classes are encouraged to improve their wrist flexion actions during the delivery.

The present study represents the first attempt to describe the kinematic characteristics of javelin-throw performed by wheelchair athletes. The results of the present study and those reported by Chow and Mindock (1999) and Chow et al. (2000a) clearly indicate that the shoulder girdle movement is a key factor in determining field event performance among wheelchair athletes. This may suggest that more emphasis should be placed on trunk movements in functional classification for wheelchair field events. Although the results indicate an overall fairness of the current classification system, more quantitative data, especially those collected during major competitions, are needed for identifying the strength and weakness of individual functional classes.

ACKNOWLEDGEMENTS

We would like to thank Randy Frommater, Todd Hatfield, Tim Millikan, and Marty Morse for their assistance in data collection.

REFERENCES

Abdel-Aziz, Y. and Karara, H. (1971) Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. In: *Proceedings of the ASP Symposium on Close Range Photogrammetry*. Fall Church, VA: American Society of Photogrammetry. 1-18.

Bartlett, R., Müller, E., Lindinger, S., Brunner, F. and Morriss, C. (1996) Three-dimensional evaluation of the kinematic release parameters for javelin throwers of different skill levels. *Journal of Applied Biomechanics* **12,** 58-71.

Chow, J.W., Millikan, T.A., Carlton, L.G., Morse, M.I., and Chae, W.S. (2001) Biomechanical comparison of two racing wheelchair propulsion techniques. *Medicine and Science in Sports and Exercise* 33, 476-484.

Chow, J.W., Chae, W.S., and Crawford, M.J. (2000a) Kinematic analysis of shot-putting performed by wheelchair athletes of different medical classes. *Journal of Sports Sciences* **18,** 321-330.

Chow, J.W., Millikan, T.A., Carlton, L.G., Chae, W.S. and Morse, M.I. (2000b) Effect of resistance load on biomechanical characteristics of racing wheelchair propulsion over a roller system. *Journal of Biomechanics* **33,** 601-608.

Chow, J. and Mindock, L. (1999) Discus throwing performance and medical classification of wheelchair athletes. *Medicine and Science in Sports and Exercise* **31,** 1272-1279.

Cooper, R. (1990) An exploratory study of racing wheelchair propulsion dynamics. *Adapted Physical Activity Quarterly* **7,** 74-85.

Depauw, K. and Gavron, S. (1995) *Disability and sport*. Champaign, IL: Human Kinetics.

Goosey, V., Fowler, N. and Campbell, I. (1997) A kinematic analysis of wheelchair propulsion techniques in senior male, senior female, and junior male athletes. *Adapted Physical Activity Quarterly* **14,** 156-165.

Ikegami, Y., Miura, M., Matsui, H. and Hashimoto, I. (1981) Biomechanical analysis of the javelin throw. In: *Biomechanics VII-B* Eds: Morecki, A., Fidelus, K., Kedzior, K. and With, A. Baltimore: University Park Press. 271-276.

Komi, V. and Mero, A. (1985) Biomechanical analysis of Olympic javelin throwers. *International Journal of Sports Biomechanics* **1,** 139-150.

Kunz, H. (1980) *Leistungsbestimmende faktoren in zehnkampf.* Zürich: ETH.

Mâsse, L., Lamontagne, M. and O'Riain, K. (1992) Biomechanical analysis of wheelchair propulsion for various seating positions. *Journal of Rehabilitation Research and Development* **29,** 12-28.

Mero, A., Komi, P., Korjus, T., Navarro, E. and Gregor, R. (1994) Body segment contributions to javelin throwing during final thrust phases. *Journal of Applied Biomechanics* **10,** 166-177.

Miller, D. and Munro, C. (1983) Javelin position and velocity patterns during final foot plant preceding release. *Journal of Human Movement Studies* **9,** 1-20.

Rich, R., Whiting, W., McCoy, R. and Gregor, R. (1985) Analysis of release parameters in elite javelin throwers. *Track Technique* **92,** 2932-2934.

Terauds, J. (1978) Computerized biomechanical analysis of selected throwers at the 1976 Montreal Olympics. *Track and Field Quarterly Review* **78,** 29-31.

Terauds, J. (1983) Biomechanics of Tom Petranoff's javelin throw. *Track Technique* **86,** 2748-2749.

Van der Wonde, L., Veeger, D., Rozendal, R., Van Ingen Schenau, G., Rooth, F. and Van Nierop, P. (1988) Wheelchair racing: Effects of rim diameter and speed on physiology and technique. *Medicine and Science in Sports and Exercise* **20,** 492-500.

Wang, Y., Deutsch, H., Morse, M., Hedrick, B. and Millikan, T. (1995) Three-dimensional kinematics of wheelchair propulsion across racing speeds. *Adapted Physical Activity Quarterly* 12, 78-89.

Wheelchair Sports, USA. (2002) *WSUSA Sanctioned Athletics Rules*. Available from URL: http://www.wsusa.org/athleticrules

Whiting, W., Gregor, R. and Halushka, M. (1991) Body segment and release parameter contributions to new-rules javelin throwing. *International Journal of Sports Biomechanics* **7,** 111-124.

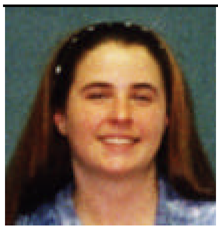
Wood, G. (1982) Data smoothing and differentiation procedures in biomechanics. *Exercise and Sport Sciences Reviews* **10,** 308-362.

Yeadon, M.R. (1989) A method for obtaining three-dimensional data on ski jumping using pan and tilt cameras. *International Journal of Sport Biomechanics* **5,** 238-247.

Yu, B. (1988) *Determination of the appropriate cutoff frequency in the digital filter data smoothing procedure*. Master's thesis, Kansas State University, Manhattan, Kansas, USA.

AUTHORS BIOGRAPHY:

John W. CHOW
Employment:
Associate Professor and Director, Biomechanics Laboratory, Depart. of Exercise and Sport Sciences, University of Florida, Gainesville, FL, USA
Degrees:
PhD.
Research interests:
Biomechanics of wheelchair sports and tennis strokes. Lower extremity functions relative to training and medical interventions.
E-mail: jchow@hhp.ufl.edu



Ann F. KUENSTER
Employment:
PhD Candidate, Department of Kinesiology, University of Illinois at Urbana-Champaign, USA
Degrees:
MS.
Research interests:
Biomechanics of wheelchair sports.
E-mail: akuenste@students.uiuc.edu

Young-tae LIM
Employment:
Assistant Professor, Division of Sport Science, Konkuk University, Chungju, Korea
Degrees:
PhD.
Research interests:
Biomechanics of wheelchair sports and golf. Musculoskeletal modeling.
E-mail: ytlim@kku.ac.kr

✉ **John W. CHOW**
Department of Exercise and Sport Sciences, PO Box 118026, University of Florida, Gainesville, FL 32611-8206, U.S.A.