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Kinematic analysis of the wheelchair tennis serve: Implications for classification

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The aim of the present study was to assess the validity of the classification system used in Open-class wheelchair tennis by investigating the relationship between post-impact ball velocity in the serve (measured using a sports radar gun) and the severity of impairment. Shoulder and wrist angles at the instant of ball impact were also estimated from 2D motion analysis. Forty-three nationally ranked Italian Open-class wheelchair tennis players were assigned to four groups (A–D) according to descending level of activity limitation. Ten successful flat serves (WFSs) and 10 successful kick serves (WKSs) for each player were recorded. One-way ANOVA showed that the severity of impairment significantly ($P < 0.05$) affected post-impact ball velocity and shoulder angle at the instant of ball impact. Furthermore, the mean value of post-impact ball velocity in WFS increased from group A to group D, i.e., with descending level of activity limitation. The results of this cross-sectional study indicate that the severity of impairment *per se* is associated with velocity of the wheelchair tennis serve, suggesting that the current classification is flawed in that it overlooks the impact of severity of impairment on players' performance.

Classification is a topic of interest within the international Paralympic Movement [International Paralympic Committee (IPC), 2007; Tweedy & Diaper, 2010]. The aim of classification in sport is to assure fair and equitable competition (Richter, 1993). The Paralympic systems of classification hence promote participation in sport by people with disabilities at the most appropriate level of rivalry by minimizing the impact of impairment on the outcome of competition (Doyle et al., 2004; Tweedy & Vanlandewijck, 2011). Impairments that meet the eligibility criteria specific for each sport are divided into classes according to the extent of activity limitation they cause. Due to the nuances of the Paralympic classification process and the considerable heterogeneity of athletes within each Paralympic sport (Tweedy, 2003; Jones & Howe, 2005; Burkett, 2010; Tweedy & Vanlandewijck, 2011), a number of researchers have questioned the classification systems used for classifying athletes with disabilities and the validity of the current systems of classification among the Paralympic sports (van Eijsden-Besseling, 1985; Firth, 1999; Tweedy, 2003; Tweedy & Bourke, 2009; Vanlandewijck et al., 2004; Gil-Agudo et al., 2010). The main concerns are related to the weighting and aggregation of measures used in classification as well as the absence of an unambiguous statement of purpose (Tweedy & Vanlandewijck, 2011). Accordingly, to address the validity of the current classification system, the IPC has mandated the development of "evidence-based classification systems through research" (IPC, 2007, item 15.2.2).

Wheelchair tennis is an intriguing example of a Paralympic sport where athletes with varying type and severity of impairment participate together. Wheelchair tennis can be defined as tennis played in a seated position (Polic, 2000). Indeed, most of the tennis principles that apply to the able-bodied game apply to wheelchair tennis, especially in areas such as strokes, grips, tactics, corrective techniques, teaching methodologies, progression, and match preparation (Filipčič & Filipčič, 2009). However, it is important to note that standing and wheelchair tennis differ in their methods of mobility (i.e., leg propulsion vs wheelchair propulsion) and generating torque and in physiological response. Wheelchair sport propulsion strategies are very complex, the movement dynamics of wheelchair tennis being specifically related to propelling the wheelchair while holding a tennis racket; moreover, two bounces are allowed for the ball in wheelchair tennis.

In tennis, the serve is the start of every point, and it is the only stroke in which the player has full control over the outcome (Bahamonde, 2000). Accordingly, the serve is considered the most important stroke in the game because it is a strong predictor of match success (Roetert & Groppel, 2001; Knudson, 2006). Sports scientists and coaches agree that the effectiveness of the tennis serve in today's high-level tennis is primarily dependent on the post-impact ball velocity (Elliot et al., 1995; Pugh et al., 2003).

The flat serve (first) and the kick serve (second) are characterized by different pre-impact racket velocity, varying in the vector components of the racket velocity (Reid et al., 2007a). In tennis, the flat serve is characterized by high ball velocity with a minimum spin, while the kick serve is considered a ball with a high amount of spin (Elliot, 1983; Chow et al., 2003). During the serve, a number of body segments must be coordinated in a sequence referred to as the "kinematic chain" to produce optimal racket position, trajectory, and velocity upon impact with the ball (Elliot et al., 1995; Roetert & Groppel, 2001). The majority of kinematic studies in able-bodied tennis serve (Bartlett et al., 1995; Elliot et al., 1995; Marshall & Elliot, 2000; Fleisig et al., 2003) have investigated selected parameters (e.g., ball velocity, joint angles, linear or angular velocities) affecting movement of the upper and lower limbs. In able-bodied tennis serve, at the instant of racket–ball impact, most of the ball velocity has been attributed to shoulder and wrist actions (Elliot et al., 1986, 1995; Gordon & Dapena, 2006).

While a wealth of information is available on tennis serve characteristics in able-bodied players, the kinematic characteristics of wheelchair tennis flat and kick serves (WFS and WKS) have been investigated very little (Reid et al., 2007b); thus, current technical instruction on the wheelchair tennis serve is largely intuitive, guided to some extent by the biomechanical information describing the able-bodied serve.

The collection of biomechanical data related to Paralympic sports performance opens up new avenues for understanding classification. Accordingly, over recent years, there has been an increased interest in the kinematics of several Paralympic sports, including track and field, basketball, cycling, swimming, and tennis (Wang et al., 2005; Frossard et al., 2007; Nolan & Less, 2007; Reid et al., 2007b; Baur et al., 2008; Lecrivain et al., 2008).

With reference to classification, no complex system exists in wheelchair tennis, and players are classified into two classes (International Tennis Federation, 2013): Quad class and Open class. In the Open class, the general eligibility criterion is that a player has a "permanent mobility-related physical disability" resulting in a "substantial loss of function in one or both lower extremities" (e.g., paraplegia, lower limb amputations or deformations). On the other hand, the Quad class includes athletes that, in addition to meeting the Open class criterion, "have a permanent physical disability that results in a substantial loss of function in one or both upper extremities" (e.g., tetraplegia). Accordingly, athletes with a wide range of activity-limiting impairments are classified in the Open class, thereby suggesting possible correlations between performance outcome and the type of impairment [e.g., spinal cord injury (SCI), amputation] and severity of impairment (e.g., spinal cord level of the lesion or complete/incomplete spinal injury). The IPC Position Stand (Tweedy & Vanlandewijck, 2011) stated that athletes should be classified according to the extent to which impairment impacts on performance. As a consequence, the current classification system might not achieve the stated purpose of classification, which is to minimize the impact of impairment on the outcome of competition. As a first step toward verifying the validity of the current wheelchair tennis classification system, this study focused on the kinematics of the tennis serve in a large sample of Open-class wheelchair tennis players to assess the relationship between a key performance outcome, i.e., post-impact ball velocity during the serve, and the severity of impairment. Moreover, other relevant kinematic parameters, namely, shoulder angle and wrist angle at the instant of ball impact, were investigated.

Methods

Participants

Forty-three nationally ranked male competitive Open-class wheelchair tennis players (mean age 33.8 ± 9.02 years) volunteered for this cross-sectional study after signing an informed consent agreement. Inclusion criteria were as follows: no severe secondary pathology that might impede performance, duration of injury (DOI) of at least 2 years, and tennis-playing experience of at least 2 years. Players ranked from 1 through 94 (median = 41) out of 94 nationally ranked athletes. Athletes had played 5.2 ± 3.62 national-level competitions in the competitive season preceding the study. Six players had played tennis at a competitive level before injury. The players had been playing wheelchair tennis for 6.7 ± 4.81 years and were involved in regular tennis competitions at an international and/or national level for at least 1 year. All participants were training regularly (2.9 ± 0.91 h of training per week). All but two subjects were right-handed. The self-reported DOI was 13.1 ± 9.42 years. The whole sample was split into four groups (A–D) on the basis of the criteria adopted by the International Stoke Mandeville Games Federation (ISMGF) (Shephard, 1988) according to descending level of activity limitation (Table 1). Groups A–C included players with complete SCI at different levels (A, T1–T5; B, T6–T10; C, T11–L3); group D included players with incomplete SCI at L4–S2, poliomyelitis (PM) affecting lower extremities ($n = 4$), and unilateral transfemoral amputation (TFA) ($n = 2$). All group D players were able to stand and/or walk with the aid of a crutch. The protocol conformed to the Declaration of Helsinki (revised in 2008). The Institutional Review Board at the University of Verona approved the study protocol.

Testing protocol

In this study, post-impact ball velocity of WFS and WKS were investigated during one regular on-court training session. During data collection, each participant used his own racket and personal wheelchair. Subsequent to a personal individual warm-up, each subject performed high-velocity WFS and WKS, with a 2-min rest period between serves. Three kinematic parameters were evaluated: the post-impact ball velocity (V_{ball}WFS and V_{ball}WKS) and the shoulder and wrist angles (S_{ang}WFS and S_{ang}WKS; W_{ang}WFS and W_{ang}WKS) at the instant of ball impact.

Table 1. Division of the sample on the basis of the criteria adopted by the International Stoke Mandeville Games Federation (ISMGF) (Shephard, 1988)

Group	*n*	Medical diagnosis	ISMGF class	Functional characteristics
A	7	Complete paraplegia at the T1–T5 level	Class II	No useful abdominal muscles; no functional lower intercostal muscles. No useful sitting balance.
B	8	Complete paraplegia at the T6–T10 level	Class III	Good upper abdominal muscles. No useful abdominal or lower trunk extensor muscles. Poor sitting balance.
C	8	Complete paraplegia at the T11–L3 level	Class IV	Good abdominal and spinal extensor muscles. Some hip flexors and adductors. Weak or nonexistent quadriceps strength, limited gluteal control.
D	5	Incomplete SCI at the L4–S2 level	Class V, Class VI	Good or fair quadriceps control.
	2	PM	Class V, Class VI	
	1	TFA	Class A2	

PM, poliomyelitis; SCI, spinal cord injury; TFA, transfemoral amputation.

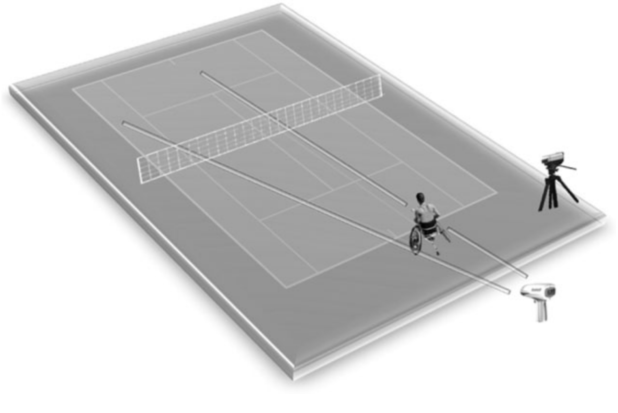

Fig. 1. Experimental setup.

V_{ball} was determined using a sports radar gun (Bushnell Speedster II radar gun; Bushnell, Overland Park, Kansas, USA). The radar gun was aligned with the server position and in the direction of the center end line of the opposite service box to guarantee a maximal cosine error of less than 10 degrees (1.5% error) (Fig. 1). A Panasonic HC-X900 camera [9.15 megapixels, 30×/700× digital zoom, 29.8–368.8 mm (16:9); Panasonic, Kadoma, Japan] was used to record the subjects' maximal effort service motions for the WFS and the WKS performed on the deuce side (right side of the baseline). The camera was placed on a tripod at a height of approximately 1.5 m and located at approximately 5 m directly perpendicular to the server's sagittal plane in order to avoid visual distortion (Fig. 1).

All services hit by the players were recorded. The entry of the ball into the box was not recorded on video, but the success of each service (i.e., landing within the opposite side of the service box, no line fault or net cord) and the landing locations of the balls delivered by the players were monitored manually. The mean velocity data from the first 10 successful WFSs and 10 successful WKSs were used for analysis. Each subject took as many trials as necessary to perform the required number of serves.

After the recording of the video images, the video material was loaded onto a PC and analysed using Dartfish 5.0 Advanced Video Analysis Software (Dartfish, Fribourg, Switzerland). Each of the 20 video clips of successful serves was rewound frame by frame and stopped at the instant of ball impact to directly estimate the shoulder and wrist angles with the digital goniometer built into the Dartfish software. The shoulder and wrist angles were scored based on the position of the upper arm relative to the trunk and the hand flexion with respect to the forearm that occurs anterior to the coronal plane (Fig. 2). The same operator took at least three readings for each trial, and the mean value was recorded when the coefficient of variation was < 0.05. Data acquisition was completed in 6 months.

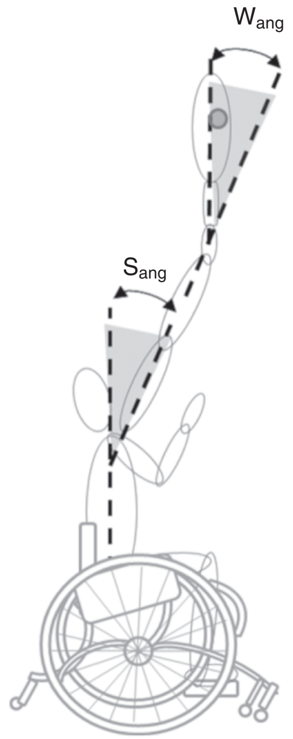

Fig. 2. Two-dimensional functional representation of the shoulder angle (S_{ang}) and the wrist angle (W_{ang}).

Statistical analysis

Statistical analysis was performed with SPSS v. 18 (IBM Corp., Armonk, New York, USA). The critical appraisal approach (Peat & Barton, 2005) was used to determine the normality of each individual's trials. No data set violated these criteria, and descriptive statistics were then calculated for each participant using standard procedures for all variables. Normality of data was assessed with the Shapiro–Wilk test ($P > 0.05$); for normally distributed variables, one-way ANOVA followed by post-hoc test with Bonferroni's correction for multiple comparisons was used to assess differences within and between groups, respectively; Levene's test was performed to validate the application of ANOVA. In the case of non-normal distribution, the Kruskal–Wallis test was used for within-group comparison, followed by the Mann–Whitney test. Each group comprised 7–8 subjects, more than in previously published similar papers on wheelchair tennis, and considering the particular population, this number is representative. Correlations between groups (A–D) and kinematic parameters were evaluated using Spearman's rho (ρ_s). Pearson's product-moment correlation coefficient (r) was used to assess the relationships between kinematic parameters. Statistical significance was set at $P \leq 0.05$.

Results

Data from 12 players were either incomplete or unreliable due to failure in adhering to the protocol requirements or due to insufficient quality of video recording; accordingly, a complete set of measurements was available for 31 players. The sample represents about 33% of all nationally ranked Italian wheelchair tennis players. The distribution of players in the four groups was as follows: group A, $n = 7$; group B, $n = 8$; group C, $n = 8$; group D, $n = 8$ (Table 1). The characteristics of the four groups are summarized in Table 2.

Within-group comparison revealed no significant difference between groups for age, DOI, tennis-playing experience, national ranking level, number of competitions at national level, or hours of training per week. Analysis of kinematic parameters showed different V_{ball}WFS and V_{ball}WKS within groups ($F = 4.141$, $P = 0.015$, and $F = 4.909$, $P = 0.08$, respectively) as well as different S_{ang}WFS and S_{ang}WKS ($F = 11.179$, $P < 0.001$, and $F = 5.321$, $P = 0.005$, respectively). W_{ang}WFS and W_{ang}WKS did not differ ($F = 1.539$, $P = 0.227$, and $F = 0.799$, $P = 0.505$, respectively). Post-hoc analysis showed greater absolute V_{ball}WFS in group D vs both A (17.21%) and B (14.32%), the difference being significant in the former ($P = 0.021$) and borderline in the latter ($P = 0.053$). The difference between group D and group C (8.81%) was not significant (Table 3). V_{ball}WKS (Table 3) showed higher mean values in group D vs A–C (16.33%, 27.44%, and 17.30%, respectively), but the difference was only significant between group D and group B ($P = 0.005$).

S_{ang}WFS and S_{ang}WKS were lower in group D than in A and B (S_{ang}WFS: −47.33%, $P = 0.002$, and −49.31%, $P < 0.001$, respectively; S_{ang}WKS: −52.76, $P = 0.036$, and −54.87, $P = 0.014$, respectively). No significant difference was found for S_{ang}WFS and S_{ang}WKS between groups D and C (−14.23% and −23.73%, respectively). S_{ang}WFS was lower in group C than in B and A (−41.48%, $P = 0.003$, and −38.59%, $P = 0.014$, respectively). A similar pattern was found in S_{ang}WKS (−40.83% vs group B and −38.06% vs group A), but the difference was not significant.

The correlations between groups (A–D) and kinematic parameters and those of kinematic parameters with each other are summarized in Tables 4 and 5, respectively. The ρ_s correlation coefficient was significant between group and V_{ball}WFS, V_{ball}WKS, S_{ang}WFS, and S_{ang}WKS ($\rho_s = 0.559$, $P = 0.001$; $\rho_s = 0.431$, $P = 0.016$; $\rho_s = -0.697$, $P < 0.001$; $\rho_s = -0.546$, $P = 0.001$, respectively). No significant correlation was found between group and W_{ang}WFS or W_{ang}WKS. Pearson's r showed a significant negative relationship between V_{ball}WFS and S_{ang}WFS

Table 2. Characteristics of the wheelchair tennis players

	Group A ($n = 7$)	Group B ($n = 8$)	Group C ($n = 8$)	Group D ($n = 8$)	Total ($n = 31$)
Age (years)	33.71 (9.23)	33.25 (6.20)	33.63 (10.57)	38.13 (11.32)	34.71 (9.29)
National ranking level (median)	78	43	49.5	31.5	39
DOI (years)	13.00 (6.73)	9.25 (7.83)	12.75 (3.85)	21.38 (15.71)	14.13 (10.28)
Tennis-playing experience (years)	6.14 (2.85)	4.38 (3.07)	6.25 (2.71)	8.38 (7.41)	6.29 (4.53)
Hours of training per week	2.57 (0.98)	3.38 (0.92)	2.63 (0.92)	3.00 (1.07)	2.90 (0.98)
Competitions at national level (n)	5.86 (1.44)	7.86 (1.36)	4.13 (1.35)	5.23 (1.35)	5.77 (3.89)

The four groups showed no statistically significant difference for any of the examined parameters.

Data are reported as mean (standard deviation), with the exception of the national ranking level, which is reported as median.

DOI, duration of injury.

Table 3. Kinematic values for ball velocity and joint angles during wheelchair tennis flat and kick serves

	Group A	Group B	Group C	Group D
V_{ball}WFS (mph)	56.63 (5.13)	58.06 (5.53)	61.00 (7.70)	66.38 (4.59)$^{*\#}$
V_{ball}WKS (mph)	50.77 (3.47)	46.35 (6.11)	50.35 (6.49)	59.06 (9.45)$^{\#\#}$
S_{ang}WFS (deg)	55.09 (12.46)	57.80 (13.88)	33.83 (11.62)$^{**\#\#}$	29.01 (10.70)$^{***\#\#\#}$
S_{ang}WKS (deg)	52.27 (20.45)	54.71 (22.97)	32.38 (14.81)	24.69 (11.39)$^{*\#\#}$
W_{ang}WFS (deg)	28.98 (9.61)	35.70 (10.59)	25.31 (9.17)	30.87 (9.92)
W_{ang}WKS (deg)	30.81 (12.99)	31.40 (11.05)	24.15 (9.24)	26.44 (10.36)

$^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.01$ vs A; $^{\#}P < 0.05$, $^{\#\#}P < 0.01$, $^{\#\#\#}P < 0.001$ vs B.

Data are reported as mean (standard deviation).

V_{ball}WFS, ball velocity during wheelchair tennis flat serve; V_{ball}WKS, ball velocity during wheelchair tennis kick serve; S_{ang}WFS, shoulder angle during wheelchair tennis flat serve; S_{ang}WKS, shoulder angle during wheelchair tennis kick serve; W_{ang}WFS, wrist angle during wheelchair tennis flat serve; W_{ang}WKS, wrist angle during wheelchair tennis kick serve.

Table 4. Spearman's *rho* correlation coefficient between group (A–D) and kinematic parameters

	V_{ball}WFS	S_{ang}WFS	W_{ang}WFS	V_{ball}WKS	S_{ang}WKS	W_{ang}WKS
ρ_s	0.559	–0.697	–0.009	0.431	–0.546	–0.197
P	0.001*	<0.001*	0.963	0.016*	0.001*	0.289

*$P < 0.05$.

V_{ball}WFS, ball velocity during wheelchair tennis flat serve; V_{ball}WKS, ball velocity during wheelchair tennis kick serve; S_{ang}WFS, shoulder angle during wheelchair tennis flat serve; S_{ang}WKS, shoulder angle during wheelchair tennis kick serve; W_{ang}WFS, wrist angle during wheelchair tennis flat serve; W_{ang}WKS, wrist angle during wheelchair tennis kick serve.

Table 5. Pearson's product-moment correlation coefficient between kinematic parameters

		S_{ang}WFS	W_{ang}WFS	S_{ang}WKS	W_{ang}WKS
V_{ball}WFS	*r*	–0.385	0.046		
	P	0.033*	0.805		
S_{ang}WFS	*r*		0.525		
	P		0.002*		
V_{ball}WKS	*r*			–0.389	–0.094
	P			0.031*	0.616
S_{ang}WKS	*r*				0.715
	P				<0.001*

*$P < 0.05$.

V_{ball}WFS, ball velocity during wheelchair tennis flat serve; V_{ball}WKS, ball velocity during wheelchair tennis kick serve; S_{ang}WFS, shoulder angle during wheelchair tennis flat serve; S_{ang}WKS, shoulder angle during wheelchair tennis kick serve; W_{ang}WFS, wrist angle during wheelchair tennis flat serve; W_{ang}WKS, wrist angle during wheelchair tennis kick serve.

($r = –0.385$, $P = 0.033$) as well as between V_{ball}WKS and S_{ang}WKS ($r = –0.432$, $P = 0.015$). S_{ang}WFS and S_{ang}WKS were positively correlated with W_{ang}WFS and W_{ang}WKS, respectively ($r = 0.525$, $P = 0.002$; $r = 0.527$, $P = 0.002$).

Discussion

The classification of athletes with disabilities is a critical issue in competition events. Open-class wheelchair tennis is mainly played by people with paraplegia or amputation who have, inter alia, various degrees of muscle power impairment at the trunk, pelvis, and hips. The present work aimed to examine the validity of the classification system currently used in Open-class wheelchair tennis by assessing possible systematic differences in a key performance outcome, i.e., post-impact ball velocity during the serve, in a large sample of players with different type and severity of impairment. In order to further explore the kinematics involved, shoulder angle and wrist angle at the instant of ball impact were assessed.

An important result of this study was that the severity of impairment of Open-class wheelchair tennis players assessed according to the ISMGF criteria influenced post-impact ball velocity and shoulder angle at the instant of ball impact in both WFS and WKS. In particular, the present data show that the mean value of post-impact ball velocity in WFS increases from group A to group D (Table 3), i.e., with decreasing severity of impairment. Therefore, it is suggested that the severity of impairment *per se* is associated with performance in the wheelchair tennis serve in players with similar age, DOI, tennis experience, national ranking level, amount of training, and number of tournaments. If performance and impairment are correlated in the Open class, impairment will have an impact on match outcome. Consequently, the successful players will be those with the least activity limitation resulting from their impairment (and not the best trained or coached).

In our sample there was no correlation between group (A–D) and national ranking. This may be due to the relatively low number of subjects in each group and heterogeneity therein; moreover, it should be taken into account that several other abilities beyond serve can influence overall performance in wheelchair tennis, such as wheelchair acceleration and agility. Nevertheless, the median ranking of group A was worse than that of group D (78 vs 31.5, Table 2), suggesting that ranking is to some extent affected by the severity of impairment; interestingly, when correlation between ranking and post-impact ball velocity was explored in the whole sample, a negative (albeit non-significant) relationship emerged ($r = –0.184$ for WFS, $r = –0.238$ for WKS) suggesting a role for serve performance in sport outcome.

Biomechanical studies related to the service technique of able-bodied high performance tennis players provided practical information on the key mechanical characteristics of this stroke (Elliot et al., 1986, 1995). The serve is commonly considered the most important stroke in the game because it is a strong predictor of match success, with its effectiveness being primarily dependent on ball velocity (Elliot et al., 1995; Roetert & Groppel, 2001; Pugh et al., 2003; Knudson, 2006). While there are inherent differences between standing and wheelchair tennis serves, such as the hitting height, the dynamic leg actions, and the extent of trunk motion, a link between service efficiency and point-winning chance can also be expected in wheelchair tennis, although it has not been investigated so far.

The kinematic chain of an effective tennis serve may involve increased maximum linear velocity of segments in a proximal-to-distal sequence from the knee to the racket (Elliot et al., 1995). Moreover, increased hitting height is a major factor in producing higher post-impact ball velocity for players of higher performance level (Bartlett et al., 1995). Maximal hitting height is reached where the body is extended with shoulder, elbow, and wrist angles approximating 180° (Girard et al., 2005). In fact, the possibility of producing optimal racket position, trajectories, and velocity upon impact with the ball depends on the extent of restriction of motion of the segments.

Compared with able-bodied players, wheelchair players obviously employ fewer segments in the serve kinematic chain as a result of the sitting position and individual impairment. In this work, wheelchair players were classified on the basis of the ISMGF. Such a medical classification implies variable lower limb function, trunk range of motion, and abdominal and spinal muscle strength and, hence, variation in trunk hyperextension and scapulothoracic motion. Accordingly, groups D and C in this study showed a more acute shoulder angle at the instant of ball impact compared with groups A and B (Table 3) for both serve types, and acute shoulder angles were associated with greater ball velocity in both serve types (Table 5), as already shown in able-bodied players (Elliot et al., 1986, 1995; Gordon & Dapena, 2006). In able-bodied players, wrist flexion is important for increasing ball velocity (Gordon & Dapena, 2006). In our sample, the wrist angle did not correlate with either the ball velocity or the severity of impairment. This may be due to the wrist movement being well preserved in all players and/or the lower hitting height in wheelchair players (independent of impairment) limiting the efficiency of wrist flexion in accelerating the racket, the wrist action being mainly exploited to direct the trajectory of the ball. Interestingly, wrist angle covaried with shoulder angle in our sample. A possible explanation is that the hand is the last body segment of a kinematic chain, so the spatial positioning of the upper arm largely determines wrist flexion.

As reported by Reid et al. (2007b), superior trunk and lower limb function enable a player to gain some "push" against the wheelchair in order to "drive upward" when serving and, more importantly, to provide a more stable platform for subsequent high-speed segment coordination. Furthermore, the lower vertebral level of injury as well as the incomplete nature of spinal cord injury in players in group D would typically imply that these players possessed superior trunk and abdominal strength as compared with players in group A–C. It seems reasonable to assume that athletes who have good trunk mobility and control will have an advantage during the tennis serve over those with absent or inferior functional trunk movement. However, some trunk strength impairment can be tolerated with minimal impact on performance in track wheelchair start (Vanlandewijck et al., 2011); accordingly, further research is required to establish the precise impact of trunk strength impairment on the wheelchair tennis serve. Trunk function influences the upper arm action from backswing to forward swing and consequently affects hitting height. In wheelchair tennis, the hitting height is clearly limited by the sitting height; further, players with compromised trunk musculature commonly increase sitting stability by using a "deep" sitting position, in which the seat surface is inclined such that the knees are brought towards the chest with an acute angle at the hips, thereby limiting the trunk motion and, consequently, hitting height. In this study, the hitting height was not measured; however, the narrower shoulder angle at ball impact found in group D and the (possible) higher sitting position could allow group D players to reach greater hitting heights vs group A–C.

In this work, 2D kinematic measurement was used, which is well suited to data acquisition in a number of settings (Frossard et al., 2005). However, accurate analysis of shoulder and wrist kinematics would benefit from 3D acquisition (Fleisig et al., 2003), and accordingly, the values of the shoulder and wrist angles presented herein should be interpreted with some caution. When interpreting our data, it should also be noted that the impact of impairment on wheelchair tennis serve velocity might differ within group D alone because of the variation in impairment type. In fact, the impact of an amputation might impact differently on performance compared to impaired muscle strength (e.g., in players with incomplete SCI). Accordingly, a ratio-scale measure of impaired strength would be more appropriate for future research on the whole population of Open-class wheelchair tennis players so that impairments of trunk and arm strength can be compared and aggregated.

While the tennis serve is clearly important to overall tennis performance, other physical factors influence tennis outcome (wheelchair acceleration, agility, training, etc.) that were not included in this study. In future studies, these measures will be considered in order to fully understand the impact of impairment on wheelchair tennis performance.

In conclusion, the present work represents the first attempt to quantify the relative impact of Open-class players' impairment on wheelchair tennis serve performance. The results suggest that the current classification system is flawed because it does not consider the impact of severity of impairment on tennis serve velocity. Despite the highly technical nature of the service stroke, the ball velocity generated is strongly dependent on the Open class wheelchair tennis player's type and severity of impairment and therefore the extent of activity limitation the impairment causes. The classification of wheelchair tennis players should be based on the relationship between the type and severity of impairment and sport performance in order to minimize the effect of activity limitation on the outcome of competition. Winning or losing an event should depend on training, talent, motivation, and skill, rather than on belonging to a favored or disadvantaged group (Richter, 1993). Given that classes must always span a range of activity limitations, the most important guiding principle for setting the number of classes should be that within any given class athletes should not succeed simply because their impairments are less severe than those of their competitors (Tweedy & Bourke, 2009). More quantitative data from a worldwide spectrum of wheelchair tennis athletes are needed to explore the factors with the greatest effect on wheelchair tennis performance and to provide an evidence-based classification system. Future research should investigate the wheelchair tennis classification system on the basis of precisely measured severity of impairment.

Perspectives

Providing an optimal sports classification system for individuals with disabilities remains a challenge. This study in wheelchair tennis highlights the critical need for research aimed at clarifying to what extent the individual player's impairment impacts on performance in Paralympic sports. The present results demonstrate a clear relationship between the player's impairment and performance in the Open-class wheelchair tennis serve, suggesting that (a) the current wheelchair tennis classification system should be challenged as to fairness and (b) a valid classification system taking into account the player's impairment as measured objectively with ratio-scaled methods should be considered.

Key words: Paralympic classification, tennis service performance, wheelchair athletes, wheelchair court sports, ball velocity, joint angle, disability.

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