



Six inertial measurement unit-based components describe wheelchair mobility performance during wheelchair tennis matches

Thomas Rietveld^{1,2} · Riemer J. K. Vegter^{1,2} · Rienk M. A. van der Slikke^{2,3} · Aldo E. Hoekstra⁴ · Lucas H. V. van der Woude^{1,2,5} · Sonja de Groot^{6,7}

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Abstract

The aim of this explorative study was to determine the key inertial measurement unit-based wheelchair mobility performance components during a wheelchair tennis match. A total of 64 wheelchair tennis matches were played by 15 wheelchair tennis players (6 women, 5 men, 4 juniors). All individual tennis wheelchairs were instrumented with inertial measurement units, two on the axes of the wheels and one on the frame. A total of 48 potentially relevant wheelchair tennis outcome variables were initially extracted from the sensor signals, based on previous wheelchair sports research and the input of wheelchair tennis experts (coaches, embedded scientists). A principal component analysis was used to reduce this set of variables to the most relevant outcomes for wheelchair tennis mobility. Results showed that wheelchair mobility performance in wheelchair tennis can be described by six components: rotations to racket side in (1) curves and (2) turns; (3) linear accelerations; (4) rotations to non-racket side in (4) turns and (5) curves; and finally, (6) linear velocities. One or two outcome variables per component were selected to allow an easier interpretation of results. These key outcome variables can be used to adequately describe the wheelchair mobility performance aspect of wheelchair tennis during a wheelchair tennis match and can be monitored during training.

Keywords Inertial measurement units · Monitoring · Technology · Wheelchair sports · Paralympics

1 Introduction

The addition of wheelchair tennis to the Grand Slam tournaments is a typical example of the inclusive sports movement during the last decades in Paralympic Sports [1, 2], i.e., the combined organization of adapted and abled-bodied sports

tournaments. Wheelchair tennis is often described as part of the wheelchair court sports, together with wheelchair basketball and wheelchair rugby [3]. However, being a non-contact sport, the availability of half the court to one or two players and the use of a racket while propelling the wheelchair sets wheelchair tennis apart from the other wheelchair court sports [4–6]. A better understanding of the actual wheelchair mobility performance during wheelchair tennis matches will benefit the development of match performance and training practice in wheelchair tennis players [7].

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✉ Thomas Rietveld
t.rietveld@lboro.ac.uk

¹ Center for Human Movement Sciences, University of Groningen, University Medical Center Groningen, Groningen, The Netherlands

² Peter Harrison Centre for Disability Sport, School of Sport Exercise & Health Sciences, Loughborough University, Loughborough, UK

³ Human Kinetic Technology, The Hague University of Applied Sciences, The Hague, The Netherlands

⁴ Royal Dutch Lawn Tennis Association, Amstelveen, The Netherlands

⁵ Center for Rehabilitation, University Medical Center Groningen, Groningen, The Netherlands

⁶ Amsterdam Rehabilitation Research Center Reade, Amsterdam, The Netherlands

⁷ Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, VU University, Amsterdam, The Netherlands

Wheelchair tennis performance can be described from two different perspectives, a wheeling and tennis performance perspective [7]. The interactive sum of the two defines actual wheelchair tennis performance. Wheeling performance can be described as the wheelchair mobility performance, the wheelchair-athlete behavior on the field, which is influenced by the propulsion technique of the athlete, the wheelchair characteristics, and environmental factors. Wheelchair mobility performance is the total set of wheeling activities of the athlete on the playing field, such as sprinting, braking, and turning [8]. Wheelchair tennis players play for about an hour per match, cover 1800–2200 m per set and reach peak velocities of 3–4 m/s [1, 9–11]. The length and intensity of the match are influenced by the level, score margin, and court-surface [9, 12]. The match characteristics and external influences roughly describe the important role of wheelchair mobility performance during a wheelchair tennis match. Inertial measurement units (IMUs) may help to describe wheelchair mobility performance more specifically during match play.

Previous research has indeed shown that wheelchair mobility performance can be reliably described and monitored during a match, in training and test settings with a combination of three IMUs [13–15]. IMUs can be attached to the frame and wheel-axes of the wheelchair and simultaneously collect gyroscope, accelerometer, and magnetometer data. These combined data can consequently be processed to attain more detailed information about the (rotational) velocities and accelerations, as well as distances covered and the number of turns per side [9, 13]. In wheelchair tennis, the maximal wheelchair mobility performance effort can adequately be measured with IMU-based field tests [16].

Outcomes of multiple (three) IMU-based data may be hard to interpret, due to the large number of variables which can be extracted. In wheelchair basketball, this large number of variables was already minimized using a principal component analysis (PCA) to six key features of wheelchair mobility performance during a wheelchair basketball match [17]. In a recent study, these key features were explored among the three wheelchair court sports [18]. It was shown that wheelchair basketball players reached higher values on the linear components (mean speed: 1.57 vs. 1.34 m/s), while wheelchair tennis players scored higher on the rotational elements of game play (mean rotational speed in curve: 72 vs. 67 deg/s). The substantial differences in match time, rest/work ratio, and distances covered were also quantified between wheelchair tennis and wheelchair basketball [19]. These studies together suggest that the character of a wheelchair tennis match might require other key features in wheelchair mobility performance compared to wheelchair basketball. The possible requirement of other features may be important for training focus of wheelchair tennis players.

The aim of this explorative study was to determine the key IMU-based components of wheelchair mobility performance during wheelchair tennis matches. These key components were determined using a PCA on a set of wheelchair mobility performance outcome variables of wheelchair tennis matches. The selected variables were based on previous research and discussion sessions with wheelchair tennis experts (coaches/embedded scientists). A sub-aim was to explore whether there are key components which are different between different player groups (men/women/juniors) in wheelchair tennis. It was expected that elite wheelchair tennis players (men/women) would obtain higher values on these components compared to talented junior players.

2 Methods

2.1 Participants

Fifteen elite Dutch wheelchair tennis players participated in this explorative study (Table 1). Four players were talented youth players (three women, one man) and the other eleven were adult players (six women, five men) playing at an international competition level. At the time of this study, the adult players had an ITF ranking for men or women, and the junior players had a ranking for boys or girls. Adult players trained for about 10–15 h per week, while the talented group trained for 4–6 h per week. The study protocol was approved by the Ethical Committee of the Center of Human Movement Sciences, University Medical Center Groningen (ECB_202000706). All participants gave written informed consent to participate.

Table 1 Participants' characteristics

Personal characteristics	N or mean (SD)	
	Adults (N=11)	Juniors (N=4)
Men/women (N)	5/6	1/3
Right/left-handed (N)	10/1	3/1
Age (years)	28.2 (7.1)	15.9 (1.3)
Impairment		
Amputation	2	1
Spina bifida	2	1
Uneven legs	2	
Spinal cord injury	3	
Caudal regression syndrome	1	1
Scoliosis		1
Weak bones	1	
ITF ranking*	15.5 (23.2)/10.0 (47.3)	6.0 (10.5)

*Median (IQR), ITF ranking is based on men/women for adults and boys/girls together (due to anonymity) for juniors

2.2 Design

All participants together completed a total of 64 wheelchair tennis matches (juniors = 11, women = 25, men = 28) on an indoor hardcourt surface (2 till 8 matches per player) in their own IMU-instrumented wheelchair. Wheelchair tennis players were measured during the full matches played in the 2018 and 2019 editions of the ABN-AMRO tennis tournament (Rotterdam, the Netherlands) and the 2018 and 2019 editions of the Dutch National Wheelchair Tennis Championships (Amstelveen/Alphen aan de Rijn, the Netherlands). The outcomes of these matches were unknown due to anonymity of the data. All individual tennis wheelchairs were instrumented with three IMUs (NGIMU, x-io technologies, Bristol, UK), one in the hub of each wheel and one on the frame of the wheelchair (Fig. 1) [16, 17, 20].

2.3 Data analysis

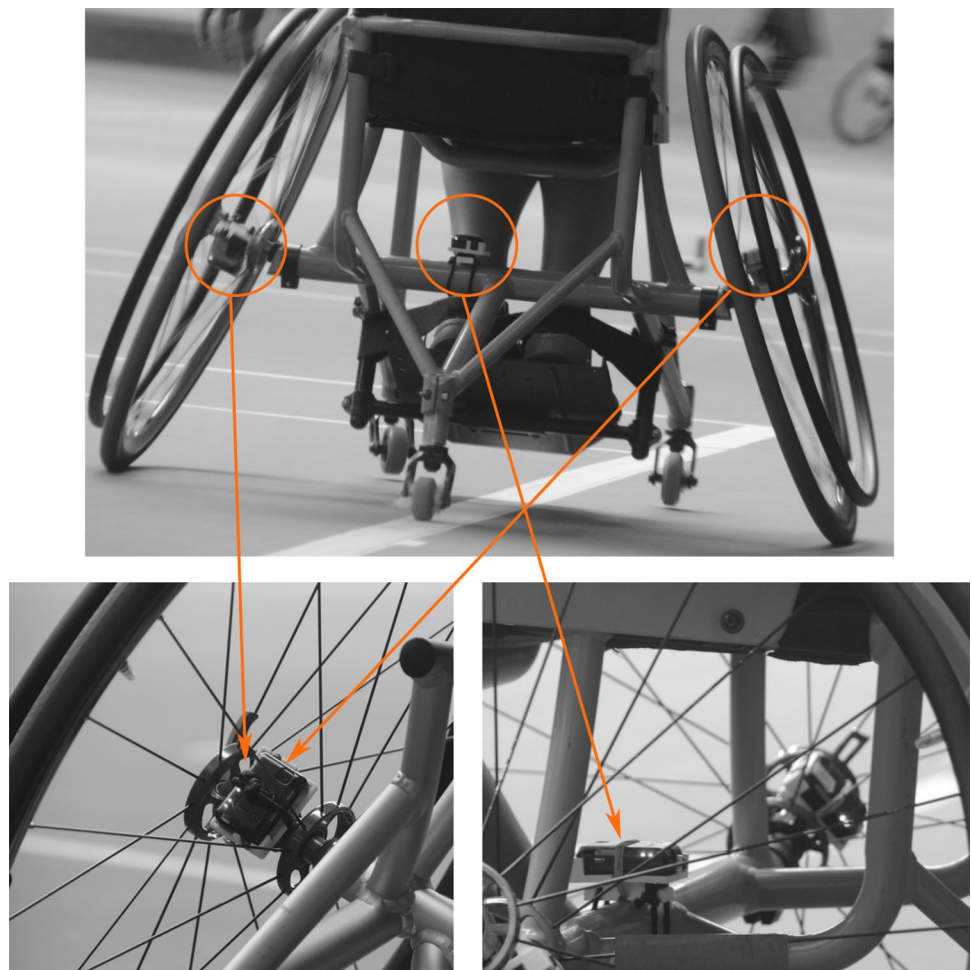
All wheelchair tennis match data were collected with a sampling frequency of 100 Hz and analyzed using custom-written Python routines [21]. The data were filtered with

a low-pass second-order recursive Butterworth filter with a cutoff frequency of 20 Hz. The three-dimensional gyroscope of the three attached IMUs was combined to derive all variables. Velocity (m/s) was calculated based on the gyroscope in the wheels, with methods previously described [13]. Taking the derivative of the velocity resulted in the accelerations (m/s^2). Integrating the velocity resulted in the distances (m). The rotational velocity (deg/s) was calculated using the IMU on the frame. Taking the derivative of the rotational velocity resulted in the rotational acceleration (deg/s^2). Consequently, these data were used to calculate 48 potentially relevant wheelchair mobility performance outcomes (Online Resource), based on previously defined algorithms [13, 15, 16].

2.4 Outcomes

All outcome variables were extracted from the IMUs on the frame and wheels during the matches. The 48 variables were a selection from outcomes used in previous studies and the input of wheelchair tennis experts (coaches, embedded scientists) [9, 17, 22–24]. More detailed descriptions of all

Fig. 1 Placement of IMUs in the hub of the wheels and on the frame in wheelchair tennis matches [20]



calculated variables can be found in Online Resource. Outcomes were calculated for actual movement (> 0.1 m/s) and rotation ($> 10^\circ/\text{s}$) times only [17]. Linear movements were split into forward/reverse direction and rotational movements were split into turns to the racket (R) and non-racket (NR) direction. Basic outcomes were calculated: the distance (m) per min, number of turns (n) per min, forward/reverse ratio, and active/rest ratio. For the velocities and accelerations in the linear and rotational direction, the mean, mean of highest five, and peak values were defined. Other variables defined were the percentage of velocity and acceleration in three zones, and the number of high-speed activations (> 2 m/s). Lastly rotational movements were split into turns and curves, with a turn being defined as rotating on the spot and a curve being rotating while pushing forward: turn1 ($- 0.5$ to 0.5 m/s), turn2 ($- 1.5$ to 1.5 m/s), curve1 ($1-2$ m/s), and curve2 (> 1.5 m/s) [17].

2.5 Statistical analysis

All statistical tests were conducted using R (4.0.1). A PCA was used as a data reduction strategy. PCA can be used in case of multiple measurements, or in this case, multiple matches per participant [25]. Pearson's correlations were used as a first step to remove highly correlated variables (> 0.85), variables most difficult to interpret were removed. Kaiser–Meyer–Olkin (KMO) analysis was performed to check the suitability for PCA. All outcome variables with a KMO less than 0.5 were removed from the analysis. Bartlett's test and KMO were performed on the remaining outcome variables to check suitability for PCA. PCA was conducted using a varimax rotation [17, 26]. The components were selected based on the eigen values (> 1), the point of inflection in the scree-plot was used as an extra control method. For each key component, the general theme (broad description of the component) was expressed by the authors. The most important variable(s) per component was selected based on the highest loading scores on the component, practical considerations and interpretations following discussions with wheelchair tennis experts. In some cases, multiple variables per component were chosen, since a component generally describes a group of variables, not just one variable.

The differences between the men, women, and juniors on the most important variables were analyzed using a one-way ANOVA on the mean outcomes per participant over the completed matches. Normality of the data was checked using the Shapiro–Wilk test [27] and visual inspections of the histograms and qq-plots. In case of non-normality, a Kruskal–Wallis test was conducted. If a significant main effect was found, post hoc tests using the 'Tukey HSD test' or 'Dunn test' were performed to analyze pairwise comparison with p value adjustments. Significance was set at $p < 0.05$ for all statistical tests. Partial eta-squared effect

sizes were calculated for the main effects, interpreted as small (0.01–0.06), medium (0.06–0.14), or large (≥ 0.14) [26]. Cohen's d effect sizes were calculated for the pairwise comparisons, interpreted as small (0.2), medium (0.5), or large (≥ 0.8) [28].

3 Results

3.1 PCA analysis

Of 48 wheelchair mobility performance outcome variables, 12 were excluded after checking for co-linearity with Pearson's correlations ($r > 0.85$). After checking the KMO values per outcome variable, another 12 variables were excluded (KMO < 0.5). The final set of 24 outcome variables was suitable for PCA (KMO = 0.70, Bartlett's test < 0.001) (Online Resource).

A total of six principal components were selected based on the PCA (total variance = 82.6%). The eigen values and explained variances of the first eight components are shown, six were higher than one (Fig. 2). The scree-plot shows a point of inflexion after four and seven components (Fig. 2).

3.2 Components

The highest 3 loading scores of the 24-wheelchair mobility performance outcome variables per component can be seen in Online Resource. General themes were assigned to the six components by the authors as: rotations to racket side in (1) curves; and (2) turns; (3) linear accelerations or high-speed activations; rotations to non-racket side in (4) turns; and (5) curves; (6) linear velocities (Fig. 3).

3.3 Key variables

One or two variable(s) per component were selected to allow an easier interpretation of results, based on the highest loading scores and valuable opinion of wheelchair tennis experts: (1) best of five rotational velocities to racket side in curve2 (> 1.5 m/s); (2) mean rotational velocity to racket side in turn1 ($- 0.5$ to 0.5 m/s); (3) mean acceleration and high-speed activations; (4) mean rotational velocity to non-racket side in turn1 ($- 0.5$ to 0.5 m/s); (5) best of five rotational velocities to racket side in curve2 (> 1.5 m/s); (6) peak reverse velocity and best of five forward velocities.

3.4 Differences among groups

The results of the men, women, and juniors on the selected key performance variables can be seen in Table 2. A main effect was found for the mean best of five rotational velocities in a curve (> 1.5 m/s) to the racket and non-racket

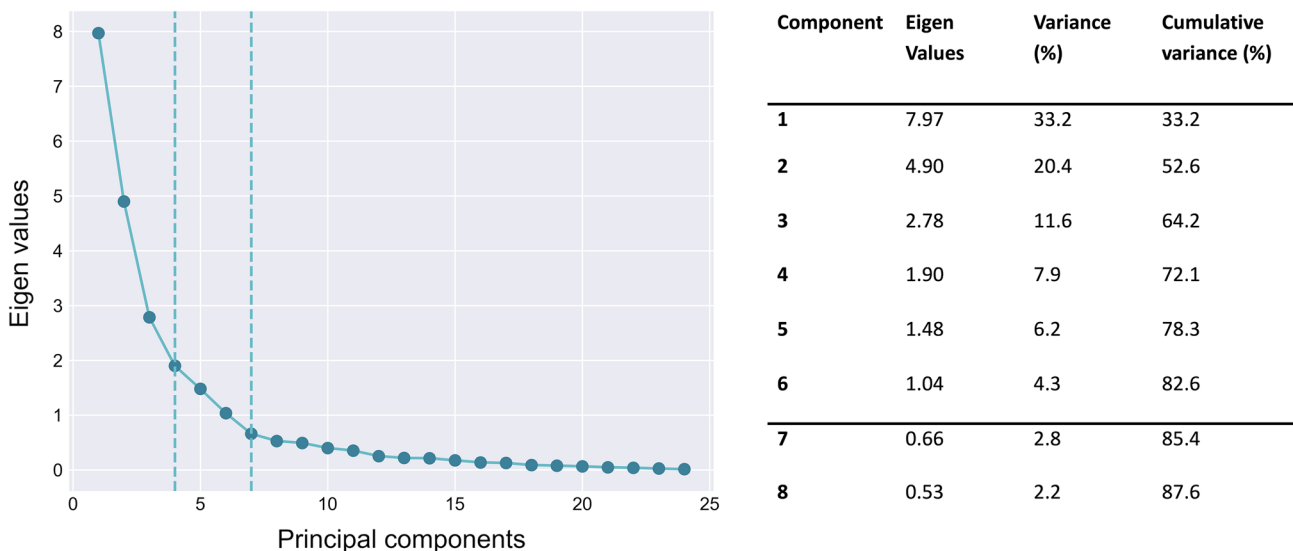


Fig. 2 Scree plot with eigen values (left). Summary of eigen values and explained variances for the first eight components (right)

Fig. 3 The general themes of the six selected principal components of the wheelchair mobility performance part during a wheelchair tennis match. A turn is defined as rotating on the spot and a curve is defined as rotating while pushing forward

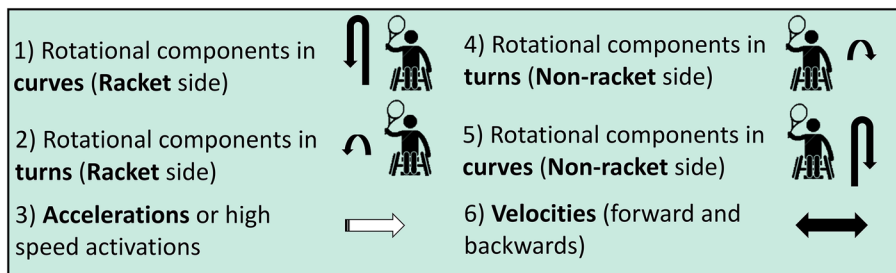


Table 2 The results (mean ± SD) on the key performance variables for the women/men/juniors including one-way ANOVA results and effect sizes

Themes	Variables	Women (n=6)	Men (n=5)	Juniors (n=4)	p	ES
Rotation to racket side in curves	Rot_vel_best5_curve2_R [deg/s]	231 (21)	252 (13)	203 (18)	<0.01	0.58
Rotation to racket side in turns	Rot_vel_mean_turn1_R [deg/s]	55 (7)	51 (7)	58 (4)	0.31	0.18
Linear accelerations or high-speed activations	# High speed activations / min	3.3 (0.7)	2.7 (0.6)	3.7 (0.5)	0.12	0.30
	Acc_mean [m/s ²]	1.10 (0.17)	1.18 (0.12)	1.25 (0.16)	0.33	0.17
Rotation to non-racket side in turns	Rot_vel_mean_turn1_NR [deg/s]	59 (7)	58 (5)	51 (6)	0.13	0.28
Rotation to non-racket side in curves	Rot_vel_best5_curve2_NR [deg/s]	221 (16)	270 (13)	235 (49)	0.04	0.42
Linear velocities	Rev_vel_peak [m/s]	1.66 (0.23)	1.84 (0.21)	1.76 (0.20)	0.42	0.13
	For_vel_best5 [m/s]	3.60 (0.15)	4.36 (0.40)	3.54 (0.40)	0.01+	0.59

Significant results ($p < 0.05$) are shown in bold.

Vel: velocity, Acc: acceleration, Rot: rotational, For: forward, Rev: reverse, Best5: best five peaks, Curve 1: 1–2 m/s, Curve 2: > 1.5 m/s, Turn 1: – 0.5 to 0.5 m/s, all: complete dataset, R: racket, NR: non-racket, +: Kruskal–Wallis test (non-normality), ES: Eta squared effect size, interpreted as small (0.01–0.06), medium (0.06–0.14) or large (> 0.15)

side, as well as the mean best of five linear velocities. Post hoc tests revealed a higher rotational velocity in a curve (> 1.5 m/s) for men vs. juniors on the racket side ($p < 0.01$, $d = 2.71$) and men vs. women on the non-racket side ($p = 0.03$, $d = 1.75$). Men also had a higher mean best of five

linear velocities compared to juniors ($p = 0.02$, $d = 2.54$) and women ($p = 0.03$, $d = 2.35$).

4 Discussion

This explorative study suggests that wheelchair mobility performance in wheelchair tennis match play can be described by six principal components. Four of these components were rotationally oriented, rotating in a curve and rotating in a turn, to the racket and non-racket side. Rotating in a curve is rotating when already in forward motion (> 1.5 m/s), while rotating in a turn ($- 0.5$ to 0.5 m/s) describes a rotation on the spot [17]. Rotations were separated for racket and non-racket side due to the influence of the racket during wheelchair propulsion in wheelchair tennis, to control for handedness, as well as the importance of rotations for hitting speeds and tactical recovery [4–6]. For the ‘Linear accelerations or high-speed activations’ component, two variables were selected. The number of high-speed activations, in other words, the number of times surpassing 2 m/s per minute can only be measured during matches and training, while the mean acceleration can be measured in matches, training, and standardized field tests [16]. The ‘Linear velocities’ component was also described by two variables, to analyze multidirectional (forward–backward) movements.

This set of six wheelchair mobility performance components describes roughly 83% of the variance during a wheelchair tennis match, adding two extra components would only add 5% of extra wheelchair mobility performance information. The presented set allows for a good balance on information, with a substantial reduction of the number of wheelchair mobility performance outcome variables, without losing too much information. The rotational components to the racket side explained 53% of the total variance, with another 14% for the non-racket side, confirming the importance of the rotational aspect in wheelchair tennis [18, 29]. Excelling on these components does not necessarily lead to a win in a wheelchair tennis match, although the relationship between winning and losing is worth to further explore. A wheelchair tennis player with an excellent technique, dictating the game, could send the opponent from one side of the court to the other, without too much movement. On the contrary, it is assumed that these wheelchair mobility performance components will make a difference during a match with small score margins during a set, since previous research showed that activity profiles are increased during these sets [9].

The key performance variable(s) per component were selected to allow an easier interpretation of results. This set of key variables should allow researchers, coaches, and players to focus on the key indicators of wheelchair mobility performance in wheelchair tennis matches, training, and field tests. Men excelled on the rotational velocities in a curve (> 1.5 m/s), as well as the linear velocities compared

to women and juniors. No clear trends were visible in the rotations in a turn (on the spot), as well as the ‘Linear acceleration and high-speed activation’ component. This sub-analysis was a first exploration of the data with a small number of wheelchair tennis players per group. With bigger sample sizes, it is expected that elite wheelchair tennis players (men/women) would excel in the wheelchair mobility performance components compared to talented junior players, based on physical characteristics and experience. Better performances in the ‘open’ class compared to the ‘quad’ class are also expected, which can be important for classification purposes [9, 16]. In wheelchair tennis field tests, the discrimination between different levels of wheelchair tennis players in wheelchair mobility performance was already reported [16]. Elite wheelchair tennis players showed higher values on the (rotational) velocity and acceleration variables compared to talented junior players [16].

In comparison to wheelchair basketball, noticeable differences were found between the identified components. The rotational aspect was an important part during a wheelchair tennis match [9, 18]. The wheelchair tennis components were described by four rotational ones, while in wheelchair basketball, only three rotational components were identified [17]. The accelerations in wheelchair tennis were more related to the mean acceleration and high-speed activations, while in wheelchair basketball, the mean acceleration was focused on the first two meters after standstill. Wheelchair tennis players are almost constantly in motion, making small rotations to racket or non-racket side, like able-bodied tennis players moving their feet. Another important difference compared to other wheelchair sports is the addition of a tennis racket during propulsion. The addition of a racket led to splitting the rotational parts in a racket and non-racket direction, while in wheelchair basketball, the average was used [17]. Since the rotational components to the racket and non-racket side resulted in different components, the differences between both sides were shown. The difference in components between sides amplifies the fact that wheelchair tennis propulsion ability, pushing while holding a racket, is an important area of interest.

4.1 Future research and implementation

In the current research, the key wheelchair mobility performance variables during a wheelchair tennis match were explored. This concept and technology can be implemented in both research and practice. Monitoring training sessions using the identified components could lead to better insights in these wheelchair mobility performance components over time, while standardized field tests could be used to test the maximal effort on these components [13]. The key components can also be used to evaluate if training or testing

sessions reflect the actual game demands. The current set of key wheelchair mobility performance components is present in previously developed wheelchair tennis field tests [16]. The Spider tests focusses on rotational components in a turn (on the spot), while the Illinois test and Butterfly Sprint test combine the linear acceleration and velocity with rotational velocity in a curve (while moving forward). The 20 m Sprint test can be seen as an excellent test for the linear acceleration and velocity components.

All wheelchair tennis athletes in this study used their own wheelchair tennis configuration in the wheelchair tennis matches, which has an influence on the interaction between the athlete, the wheelchair, and its environment. All wheelchair tennis matches were played on an indoor hardcourt surface. Different court surfaces influence wheelchair mobility performance outcomes, both linear sprinting and turning, making surface type an important area of interest for future research [12, 20]. Wheelchair tennis athletes could be tested on the key components during standardized field tests on a hardcourt surface to gather valuable insight on tennis-specific wheelchair configurations, such as the use of a new hand rim, similar to studies performed in wheelchair basketball [30–32].

The current research only focused on the wheeling part of wheelchair tennis. The tennis part (strokes/serves) of wheelchair tennis still needs exploring. Sensors can already be used to detect trunk and shoulder kinematic during strokes (backhand) [33]. Extending the current inertial measurement unit wheelchair set-up with additional sensors on the trunk/arm/wrist would collect additional information, potentially leading to external delivered power [20]. An average rally duration in wheelchair tennis takes about 9 s, similar to about four strokes [1]. Given the short average rally duration, this also sets the need for more research around wheelchair tennis serves. Sensors can also be used to analyze the positioning of the server/returner. Combining the information of the wheelchair mobility performance with the video material of tennis performance (strokes/serves) and the actual match results would give an overall performance view on the wheelchair tennis game.

4.2 Limitations

All wheelchair mobility performance variables were based on the linear and rotational velocity signals during actual wheelchair movement (> 0.1 m/s, > 10 deg/s). Since no clear distinction was made between the actual game play and movements between games, the data need to be interpreted with care. A principal component analysis is also highly dependent on the initial variable selection, which could have influenced the results. A combination of performance indicators from previous research and input from wheelchair tennis

experts led to a broad variety of variables included in the analysis. The opinion of wheelchair tennis experts was valuable at the initial variable selection, as well as the selection of the key themes and variables from the components. The current research has a balance between methodology and practicality, still qualitative research in wheelchair tennis is worth investigating.

Splitting the data set in a racket/non-racket rotation led to the inclusion of many rotational values and could have influenced the number of rotational components found. On the contrary, if the rotational values would have described the same variance, they would have been grouped as the same component. Lastly, a diverse group of athletes (men, women, juniors) was tested, which led to a preliminary discriminative analysis. The number of players per group, as well as the diverse number of matches per player could have influenced the results. Extending the number of games per player and players per group, as well as the inclusion of players of the quad division would help to generalize the results further.

5 Conclusion

Wheelchair mobility performance in wheelchair tennis can be described by a set of six key components. Four of these components were related to rotational aspects in a curve/turn for both racket/non-racket side. The other two components are representative for the linear velocity and accelerations during a match. Men reached significantly higher values on the rotational velocities in a curve (> 1.5 m/s), as well as linear velocities compared to women and juniors. The final set of six components can be used to analyze the wheeling performance of wheelchair tennis players in wheelchair tennis matches, training, and field tests.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12283-023-00424-6>.

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Data availability All relevant data are within the paper and its supporting information.

Declarations

Conflict of interest None.

Research involving human participants It is stated in the methods section: ‘The study protocol was approved by the Ethical Committee of the Center of Human Movement Sciences, University Medical Center Groningen (ECB_202000706).’

Informed consent It is stated in the methods section: ‘All participants gave written informed consent to participate.’

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