

**Out of the lab, onto the court**  
**Wheelchair Mobility Performance quantified**

van der Slikke, Rienk

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A close-up, low-angle photograph of a bicycle's rear triangle. The frame is made of silver-colored metal tubes. A white, rectangular sensor device with an orange circular light on its top surface is mounted to the frame. The background is a blurred blue sky.

# Out of the lab, onto the court

Wheelchair Mobility  
Performance quantified

Rienk van der Slikke

# Out of the lab, onto the court

## Wheelchair Mobility Performance quantified

Rienk Michiel Arjen van der Slikke

With support of:



Research project partners:



*Out of the lab, onto the court. Wheelchair Mobility Performance quantified.*

Dissertation at the Delft University of Technology

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# Out of the lab, onto the court

## Wheelchair Mobility Performance quantified

Dissertation

for the purpose of obtaining the degree of doctor  
at Delft University of Technology  
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen;  
Chair of the Board for Doctorates  
to be defended publicly on

Friday May 25<sup>th</sup> 2018  
at 10:00 o'clock

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” One day we die, most days we don't.  
Let's drag life by the hair.”

- Bart van der Weide, Raccoon -

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# Summary

Dutch Summary





## Summary

Performance in wheelchair court sports is to a large extent determined by the **wheelchair mobility performance** (WMP), the performance measure for the wheelchair-athlete combination. So far, wheelchair mobility performance is mostly utilized as concept, rather than a well quantified measure. However, in order to gain insight in the interaction between *athlete*, *wheelchair* and *sport*, it should be an objective and well quantified outcome that is easily measured.

Performance in wheelchair sports is determined by the interaction between *athlete*, *wheelchair* and *sport*. The wheelchair is an extension of the athlete and should therefore be included in the performance measurement, but it brings in its own characteristics and effects on performance. Entangling the interactions between *athlete*, *wheelchair* and *sport* supports both the wheelchair sports in general, as well as the quest of an individual athlete to improve performance and reduce injury risk. Sports-wide it helps to characterise physical demands per sport, help improve the fairness of the game by defining the true impact of impairment on performance and supports wheelchair experts in sport specific wheelchair design. In individual or team use it could support in evaluating interventions in training, wheelchair configuration and team composition.

An inertial sensor-based “**Wheelchair Mobility Performance Monitor**” (WMPM) was developed that met the demands of objective quantification of mobility performance in an easy to use manner. Comparison to an opto-kinetic motion analysis system proved the WMPM to be reliable for estimation of wheelchair kinematics, once a wheel skid correction algorithm was added. Application of the WMPM in wheelchair basketball match play showed the ease of use, while the results could be enforced to find key kinematics of the sport. These key outcomes were merged into a WMP-plot, showing the performance relative to the group for six kinematic variables, three regarding forward movement and three regarding rotational movement.

The measurement accuracy of the WMPM enabled to extract differences in performance in match play compared to sport specific field test measurements. These performance differences encountered provided insight in the relationship between maximal performance (field test) and performance shown within the limitations of match play. This insight led to the conclusion that in wheelchair basketball a reduction of impairment classes used seems viable, if only regarding wheelchair mobility. The more standardised performance testing (compared to match play) also enabled research into the effects of changes in wheelchair setting. Based on tests with 20 athletes, it could be concluded that altering seat height had some effect on speed; adding weight had effect on forward speed and acceleration; distributed added weight also had an effect on rotational speed and acceleration; and that additional hand rim grip hardly affected performance.

Towards future research, the method was applied for a comparison between the three main wheelchair sports (wheelchair rugby, basketball and tennis), showing lowest performance outcomes for wheelchair rugby and highest outcomes for wheelchair basketball. Wheelchair tennis performance ranges in-between the other two, except for rotational speeds, that were similarly high as in wheelchair basketball. So, the use of the WMPM could be extended across wheelchair sports, but the WMPM itself could also be extended by adding outcomes or functionality. More detailed signal analysis could be employed to calculate kinematics that relate to the athlete's activity, as shown by the example of calculated push characteristics in straight sprinting. A method that sheds light into the relationship between wheelchair mobility performance and the underlying activity patterns, is a very powerful tool for setting up evidence-based guidelines for classification, training, prevention of over-use injuries, and so on. To relate wheelchair mobility performance to field position, the method was combined with an indoor tracking system. Both systems showed good similarity on mutual outcomes as measured in wheelchair basketball match play, but provide complementary outcomes. So, possibly a combination of techniques could be the ultimate wheelchair mobility performance tool.

The developed Wheelchair Mobility Performance Monitor is believed to be a valuable tool for wheelchair court sports practice and research. All research performed with the WMPM showcases its opportunities and commenced the unravelling of the complex interactions between *athlete*, *wheelchair* and *sport*. It will be a matter of time before the use of the WMPM will be common practice in wheelchair sports and sports research.



## Samenvatting

De prestatie in rolstoelveldsporten wordt voor een groot deel bepaald door de “Wheelchair Mobility Performance” (WMP), de prestatie maat voor de atleet-rolstoel combinatie. Tot op heden is “wheelchair mobility performance” vooral toegepast als concept en niet zozeer als een goed gekwantificeerde maat. Voor het verkrijgen van inzicht in de relatie tussen *atleet*, *rolstoel* en *sport*, is een objectieve goed gekwantificeerde maat noodzakelijk, die bovendien makkelijk meetbaar is.

De interactie tussen *atleet*, *rolstoel* en *sport* is bepalend voor de prestatie in rolstoelsporten. De rolstoel is als het ware een verlengstuk van de atleet en moet meegenomen worden in de prestatiemeting, maar brengt ook weer zijn eigen eigenschappen en effecten op de prestatie mee. Het ontwarren van de interacties tussen *rolstoel*, *atleet* en *sport*, is van waarde voor de rolstoel sport in het algemeen, maar helpt ook de individuele atleet in zijn pogingen om prestatie te verbeteren en overbelasting blessures van de schouder te voorkomen. Rolstoel sport breed ondersteunt deze methode het verkrijgen van inzicht in de fysieke eisen die er per sport gesteld worden en het kan ondersteunen bij het eerlijker maken van de sport, door het ware effect van beperkingen op prestatie in beeld te brengen. Tenslotte kan het rolstoel experts ondersteunen in het optimaliseren van het rolstoel ontwerp per sport. Bij individueel gebruik is het concept toepasbaar om interventies te evalueren in training, rolstoel instellingen of team samenstelling.

De op inertiële sensoren gebaseerde “Wheelchair Mobility Performance Monitor” (WMPM) is ontwikkeld om op eenvoudige en objectieve wijze de “mobility performance” te kunnen meten. In een vergelijk met een opto-kinetisch camera system, is de WMPM betrouwbaar gebleken voor het berekenen van rolstoel kinematica, mits er een slip correctie toegepast wordt. Het toepassen van de WMPM tijdens rolstoelbasketbal wedstrijden gaf inzicht in welke kinematische kenmerken van belang zijn, en dat deze op eenvoudige wijze met het systeem te vergaren zijn. De zes voornaamste uitkomsten zijn samengevat in een WMP-plot, die de relatieve prestatie van een atleet ten opzichte van de totale groep toont. Er zijn 3 uitkomsten rond voorwaartse bewegingen opgenomen en 3 rond rotatie.

Met het oog op toekomstige onderzoeksprojecten, is de methode al toegepast bij drie rolstoelsporten (rolstoelrugby, -basketbal en -tennis), waaruit bleek dat de WMP bij rolstoelrugby het laagste ligt en bij rolstoelbasketbal het hoogste. De prestatie van de rolstoel tennissers ligt er tussenin, alleen de rotatiesnelheden zijn vergelijkbaar met die van rolstoelbasketbal. De WMPM is dus rolstoelsport breed toepasbaar, maar de methode is ook nog verder uit te breiden met sport specifieke uitkomsten. Meer gedetailleerde signaal analyse biedt de mogelijkheid om nieuwe kinematische kenmerken te berekenen, die meer informatie bevatten over het activiteitenpatroon van de atleet, zoals bijvoorbeeld de gepresenteerde uitkomsten rond aandrijftechniek in een sprint. Een methode die inzicht geeft in de relatie tussen WMP en de onderliggende activiteitenpatronen is belangrijk voor opstellen van

“evidence based” richtlijnen rond de classificatie, trainingsprotocollen het voorkomen van overbelasting, etc. Voor het vergelijken van de kinematische uitkomsten met de positie op het veld, zijn gecombineerde metingen uitgevoerd met een “Indoor Tracking System” (ITS). De gevonden overeenkomst voor de gemeenschappelijke uitkomsten was goed, maar de WMPM is wel van toegevoegde waarde door de extra uitkomsten rond (rotatie-) versnellingen. Wellicht is met een combinatie van beide methodes een optimale methode voor het evalueren van rolstoel veldsporten te creëren.

De ontwikkelde WMPM wordt gezien als een belangrijke ontwikkeling voor de rolstoel sportpraktijk en onderzoek. Al het uitgevoerde onderzoek geeft goed weer wat de meerwaarde van de methode is en welke mogelijkheden er nog in het verschiet liggen om de complexe interacties tussen *atleet, rolstoel en sport* verder te ontwarren. Het is een kwestie van tijd voordat het gebruik van de WMPM gemeengoed zal zijn in rolstoelsport en sportonderzoek.



# Chapter 1

General Introduction



## Chapter 1: General introduction

Increasing professionalism in wheelchair court sports demands optimisation of all factors contributing to team performance, like team interplay and individual athlete performance. The athlete's performance in turn can be sub-divided in physical performance, mobility performance and game performance. Game performance is an overall measure and defined as the true quality of an athlete's contribution to the game (Byrnes & Hedrick, 1994). Physical performance only concerns the athlete (Bloxham, Bell, Bhambhani, & Steadward, 2001), whereas mobility performance is the measure for the combined wheelchair-athlete combination (Mason et al., 2013). Therefore, although mobility performance is established by athlete exertion, it is often expressed in terms of wheelchair kinematics. This thesis comprises the quantification of **Wheelchair Mobility Performance (WMP)** in wheelchair basketball, the measurement methods needed (a WMP-monitor), it's use for optimizing sports performance, it's use for development of the game and opportunities for neighbouring wheeled sports.

In wheelchair sports, it is the interaction between athlete and chair that enable wheelchair propulsion and the movements on the sports court required within a given sport (Goosey-Tolfrey, 2010). So, in optimizing performance in wheeled sports, three components and their interactions (Figure 1.1) need to be taken into account: the *athlete*, the *wheelchair* and the *sport*.

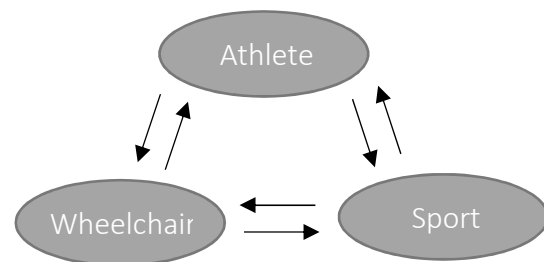


Figure 1.1: Athlete – wheelchair – sport interaction

Each of these three components have their own characteristics with an effect on overall performance, but always in interaction with the other components. Simply building more muscle power (*athlete*) for example, does not necessarily lead to higher wheelchair speeds (*sport*), if the chair is not configured properly (*wheelchair*). So, the optimization of certain performance tasks (such as improving maximal speed), cannot be done by isolated perfection of each component, but has to be approached with all components taken into account. That overall interaction identifies the main challenge in wheelchair sports related research, since it hardly allows for isolated manipulation of a single factor if done in an ecologically valid way.

The characteristics of the *athlete* can be summarized in training status, anthropometric data and impairment level as expressed in the classification. For the *wheelchair*, the characteristics are determined by the properties and settings, like seat height, seat position, camber angle, track width, wheel diameter, and so on (Mason, van der Woude, & Goosey-Tolfrey, 2013). The characteristics of a specific sport, like court size, flooring, team or individual game play, determine performance demands, summarised in the *sports* component. This component is sport specific, but can also vary between athletes within a sport, for example due to variation in classification or team roles.



In most cases, the performance targets will arise from the sport, in combination with the athlete capacities. In wheelchair basketball for example, more impaired athletes (low classification) typically fulfil more defensive roles, whereas the least impaired players occupy offensive field positions, resulting in different performance targets. Those individual performance targets comprise speed & acceleration; manoeuvrability; stability; and reach (van Breukelen, 2014), of which the first two most closely relate to wheelchair mobility performance. If the athlete characteristics are known and the performance targets (sport) are set, an optimisation of the third component (*wheelchair*) could be aimed at. Yet, a prerequisite to targeted optimisation is the availability of quantitative performance measures and insight in the relationships between the interaction of *athlete*, *wheelchair* and *sport*. These relationships need to be quantified in the most ecological valid way, implying research with the use of the *athlete's* own *wheelchair* and in *sports* specific conditions.

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Out of the lab, onto the field for quantification of wheelchair mobility performance.

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#### Quantification of Wheelchair Mobility Performance

To date, wheelchair mobility performance is mostly considered and utilized as a concept, instead of a well quantified measure. With regard to activities, mobility performance during a match can be described based on systematic observation (de Witte, Hoozemans, Berger, van der Woude, & Veeger, 2016). With more focus on kinematic aspects of mobility performance, Sarro et al. used video tracking (Sarro, Misuta, Burkett, Malone, & Barros, 2010) and Rhodes et al. (2015) presented an accurate iGPS system for measuring field position and speed profiles. Yet, none of these methods provide a comprehensive overview of kinematics needed, to accurately describe the effect of *athlete-wheelchair* interactions on performance in *sport*. Moreover, none of these methods quantify higher order outcomes, like (rotational) acceleration, which are known to be of considerable importance for wheelchair sports (Fuss, 2012). Therefore, the first step in this research project was to develop a method that was applicable in on-court measurements, providing a complete, yet concise set of key performance outcomes that could be measured in a reliable way.

The newly developed inertial sensor-based method is easy to use but brings forth a very comprehensive set of wheelchair kinematic outcomes, that are hard to handle in sports practice. Therefore, statistical methods were employed to reduce those outcomes to a set of six key kinematic outcomes, that are clearly displayed in a Wheelchair Mobility Performance plot. The full range of outcomes can be used for expansion of general mobility performance

knowledge and data science approaches, whereas the WMP-plot is also applicable for individual use, with information understandable to athletes and coaches. The new method enables evaluation of interventions regarding changes in wheelchair setting or training routines, again both on group level as well as for individual application. To provide athletes with information that could be employed to optimize performance conditions, the effect of wheelchair settings (seat height, weight distribution and hand rim grip) on wheelchair mobility performance was investigated. Showing these general relationships helps the *athlete* to optimize the *wheelchair* for the performance targets that arose from the *sport*. Furthermore, wheelchair mobility performance profiles of match measurements of different sports, supports identification of key performance targets per sport. For the main wheelchair court sports (basketball, rugby and tennis) groups of athletes were measured in match play and typical WMP profiles displayed. WMP-plots of key performance outcomes per wheelchair sports could also be used to improve fairness of the game by evidence-based classification and it could support in rehabilitation, by redirecting new wheelchair users to a sport that best fits his/her capacities. Finally, the new method allowed for an evaluation of the current classification guidelines in wheeled court sports, since the effect of impairment on wheelchair mobility performance was objectively quantified (in wheelchair basketball).



Figure 1.2: Inertial Measurement Units (IMUs) placed on the wheelchair during match play (Photograph by [www.frankvanhollebeke.be](http://www.frankvanhollebeke.be)).

Objective of this thesis

The objective of this thesis was to enhance wheelchair sports by the development and application of tools for mobility performance measurement. To enhance the sport, federations, sport scientists, coaches and athletes need: 1) insight in individual athlete performance; 2) pointers for key aspects of performance; 3) insight in the wheelchair-athlete interaction with performance; 4) insight in the performance demands per sport.

Thus, the overall objective could be divided in four sections with corresponding objectives.

The **first objective** was to develop a reliable and valid method to measure wheelchair mobility performance, applicable in all conditions. Once this method (Wheelchair Mobility Performance Monitor; WMPM) was established, it enabled research into the wheelchair mobility performance during basketball. Since the project is aimed at sports practice, the **second objective** was to reduce measurement outcomes to key features of wheelchair mobility performance, to make it more accessible for coaches and athletes. The **third objective** was to provide insight in the relationship between athlete-wheelchair characteristics and wheelchair mobility performance. This information could be used by athletes and coaches for individual performance perfection and it could be employed for evaluation of wheelchair classification guidelines. The **fourth objective** was to provide insight in differences between wheelchair court sports, which is believed to be of use in rehabilitation for referring rehabilitants to a sport that meet their capacities, but also in sports wheelchair design.

Outline of this thesis

#### *Quantification of wheelchair mobility performance (objective 1)*

A quantitative estimation of wheelchair mobility performance is needed if it is utilized as measure for evaluation of athlete training routines or changes in wheelchair configuration. To fulfil this need, a new inertial sensor-based measurement method was developed and tested for reliability regarding prime outcomes like distance covered; speed; accelerations; rotations; rotational speed and rotational accelerations (**chapter 2**). Although applied wheelchair sport wide, initially the method was developed for wheelchair basketball application. The use of the method in wheelchair basketball competition raised issues typical for match play, demanding additional optimisation for these harsh conditions (**chapter 3**).

#### *Wheelchair mobility performance characteristics in wheelchair basketball (objective 2)*

Once an unobstructive and reliable method for measuring wheelchair kinematics in all conditions was established, subsequent actions were needed to reshape it in to a useful and accessible method for athletes and coaches. The first and most important step was to reduce the number of outcomes to key features of wheelchair mobility performance (**chapter 4**), resulting in the Wheelchair Mobility Performance Monitor (WMPM). This feature reduction was initially aimed at performance in wheelchair basketball, so although the measurement method is applicable for all wheelchair sports, the outcomes not necessarily represent the key outcomes for each sport (see objective 4).

The developed WMPM enabled individual performance measures in all conditions, empowering athletes and coaches to monitor wheelchair mobility performance in subsequent matches and training sessions. Yet, these outcomes were based on the athlete-wheelchair interaction, but also influenced by match or training specific factors. If the aim is to evaluate interventions in wheelchair configuration or training, a more standardized test setting is

needed. The Wheelchair Mobility Performance field test for wheelchair basketball (*chapter 5*) was developed for such application and tested for reliability with the WMPM (*chapter 6, appendix I*). These type of field-based monitoring tools can be used at regular intervals at key time points throughout the year, to help with training evaluation (Goosey-Tolfrey & Leicht, 2013).

*Relate WMP to athlete, wheelchair or interaction (objective 3)*

The inertial sensor-based method, opened up a wide range of opportunities for the individual athlete, but also for professionalization of wheeled sports in general. One of the recurring topics in all Paralympic sports is the fairness of the game. In most Paralympic sports, a classification system is used to attain fair competition between athletes with various levels of impairment (Tweedy & Vanlandewijck, 2011). The WMPM was used in match conditions and in the wheelchair mobility performance field test to determine the relationship between classification and performance, and to stipulate the additional value for objective performance measures for an evidence-based classification system (*chapter 6*).

For support of the individual athlete, the effect of key wheelchair configurations was tested within the wheelchair mobility performance field test (*chapter 7*). Knowledge about the effect of hand rim grip, weight, weight distribution and seat height on wheelchair mobility performance was presented, so athletes and wheelchair experts could make well motivated decisions in tuning the wheelchair for the athlete specific needs.

*Wheelchair sports wide application (objective 4) and future perspectives*

At the onset of this research project, there was a focus on wheelchair basketball. Yet, the method and principles were applicable to all court sports. So, as a first step towards application across wheelchair sports, match measurements with the WMPM were performed at elite level with wheelchair rugby, wheelchair tennis and wheelchair basketball athletes during international tournaments (*chapter 8*).

The development and application of the WMPM led to a whole new research area and novel questions from sports practice. Outcomes were used for individual performance optimisation, sport specific improvements as well as optimisation across sports. To link wheelchair mobility performance outcomes to team tactics however, the missing feature was field position. Therefore, research was conducted to compare speed outcomes of the WMPM to an indoor tracking system that has been applied for wheelchair sports over the last few years (*chapter 9*). This study showed the additional value of the WMPM, but also opportunities for an integrated method, combining the best of both systems.

A final step towards the development of an ultimate wheelchair mobility performance tool was the addition of more specific outcomes regarding performance. Initially the aim of the WMPM was to quantify performance by means of measuring wheelchair kinematics, yet detailed signal analysis also allows to calculate characteristics regarding the input of the athlete, by means of

push characteristics and power output estimates. This concept is drawn up by the development of an algorithm for calculating push characteristics in a straight sprint (*chapter 10*). The current WMPM outcomes provided insight in the relationship between performance and athlete-wheelchair characteristics, but more detailed outcomes could help identify the cause of those relationships. For example, if lowered seat height is known to increase maximal speed (relationship), is that accomplished by an increase of push frequency or by an increase of push length (cause)?





# Chapter 2

## Measuring wheelchair kinematics

Opportunities for measuring wheelchair kinematics in  
match settings; reliability of a three-inertial sensor  
configuration. *Journal of Biomechanics*



## Chapter 2: Measuring wheelchair kinematics

### Opportunities for measuring wheelchair kinematics in match settings; reliability of a three-inertial sensor configuration

Slikke, van der R. M. A., Berger, M. A. M., Bregman, D. J. J., Lagerberg, A. H., & Veeger, H. E. J.

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#### Abstract

Knowledge of wheelchair kinematics during a match is prerequisite for performance improvement in wheelchair basketball. Unfortunately, no measurement system providing key kinematic outcomes proved to be reliable in competition. In this study, the reliability of estimated wheelchair kinematics based on a three-inertial measurement unit (IMU) configuration, was assessed in wheelchair basketball match-like conditions. Twenty participants performed a series of tests reflecting different motion aspects of wheelchair basketball. During the tests, wheelchair kinematics were simultaneously measured using IMUs on wheels and frame, and a 24-camera optical motion analysis system serving as gold standard. Results showed only small deviations of the IMU method compared to the gold standard, once a newly developed skid correction algorithm was applied. Calculated Root Mean Square Errors (RMSE) showed good estimates for frame displacement ( $RMSE \leq 0.05m$ ) and speed ( $RMSE \leq 0.1m/s$ ), except for three truly vigorous tests. Estimates of frame rotation in the horizontal plane ( $RMSE < 3^\circ$ ) and rotational speed ( $RMSE < 7^\circ/s$ ) were very accurate. Differences in calculated instantaneous rotation centres (IRC) were small, but somewhat larger in tests performed at high speed (RMSE up to 0.19m). Average test outcomes for linear speed (ICCs > 0.90), rotational speed (ICC > 0.99) and IRC (ICC > 0.90) showed high correlations between IMU data and gold standard. IMU based estimation of wheelchair kinematics provided reliable results, except for brief moments of wheel skidding in truly vigorous tests. The IMU method is believed to enable prospective research in wheelchair basketball match conditions and contribute to individual support of athletes in everyday sports practice.

## Introduction

Wheelchair sport events have become more and more competitive, and winning a Paralympic championship nowadays requires a professional approach. Increased professionalism in wheelchair basketball has raised the need for scientific input into the optimization of the wheelchair-athlete interaction. Wheelchair-athlete optimization requires not only insight into the general relationship between wheelchair settings and performance, it also requires knowledge of individual performance characteristics of athletes during a match (Mason et al., 2013). A method for measurement of wheelchair kinematics in match play would allow for applied research into the relationship between kinematics and performance. That knowledge could provide basis for more precise and faster optimization of individual wheelchair settings and thereby support existing experience-based expertise.

Wheelchair related performance in court sports is strongly determined by linear and rotational accelerations (Mason et al., 2013). Albeit, these acceleration data only provide performance insight if situated within the overall movement patterns, so that accurate determination of derivatives is required as well. Accelerations and rotational speed are well measured with inertial measurement units (IMU), but for reliable derivatives more complex algorithms are required. Once available, this will allow the application of IMUs for measuring kinematic aspects in sport specific situations.

While research on the effect of wheelchair settings and propulsion techniques on wheeling performance is available, data were mainly obtained with able-bodied individuals in artificial circumstances and hardly ever sport specific. The effect of propulsion techniques (van der Woude, Bakker, Elkhuizen, Veeger, & Gwinn, 1998), seat height (Masse, Lamontagne, & O'Riain, 1992) and axle position (Boninger, Baldwin, Cooper, Koontz, & Chan, 2000) on performance during normal wheeling is well investigated. The apparent subsequent step in research is the introduction of ambulatory methods, measuring *individual* sports performance in an *easy* and *affordable* manner.

No methods are yet applicable and validated for measuring all wheelchair kinematics in court sports. Mason and Rhodes (Mason, Rhodes, & Goosey-Tolfrey, 2014; Rhodes, Mason, Perrat, Smith, & Goosey-Tolfrey, 2014) presented an accurate iGPS system for measuring field position, but the available sample frequencies (max. 16Hz) do not allow for detailed analysis of speed and acceleration. Other more detailed measurement systems are often restricted to lab-based settings on a treadmill or ergometer, and thereby have limited ecological validity for wheelchair related performance research (Mason et al., 2013). Ambulatory measurement systems, like IMUs mounted on a wheelchair, can provide good estimates of distance covered, average speed and duration of movement (Coulter, Dall, Rochester, Hasler, & Granat, 2011; Sonenblum, Sprigle, Caspall, & Lopez, 2012). However, this has only been tested at moderate speeds. Pansiot, Zhang, Lo, & Yang (2011) found reliable results at moderate performance speeds for estimating velocity, heading, distance covered and trajectory, using

gyro/accelerometers in both rear wheelchair wheels during a lab-based figure 8 trajectory test. Inspired by this method, this research was dedicated to develop and test an IMU based measurement method that also enables reliable measurement of the more dynamic aspects of wheelchair use, as seen in elite level wheelchair sports.

To enable applied research and optimization of athlete-wheelchair interaction, this study seeks to provide a reliable, robust and easily applicable system to measure wheelchair kinematics during matches. To determine whether this goal is met, the IMU configuration is tested against an optical 3D system, with variedly skilled athletes in a series of tests reflecting all kinematic aspects of a wheelchair basketball match.

## Methods

Twenty participants (Table 2.1) performed a series of tests in an IMU instrumented wheelchair, while measured simultaneously with a 3D optical motion analysis system as gold standard. Calculated outcomes of wheelchair kinematics based on IMU and gold standard were compared to test the reliability of the IMU sensor configuration.

### *System overview*

A Celeritas 300 wheelchair was equipped with 3 markers and 3 battery powered inertial measurement units (x-IMU; x-io Technologies) measuring 3D linear acceleration, angular velocity and magnetic field orientation at a sampling rate of 256 Hz. Sensors were placed on the frame's rear axis slightly right from the centre and on each wheel axis (Figure 2.1). Data were collected on micro-SD cards, with initial factory registry-settings used ( $\pm 8g$  for the accelerometers and  $\pm 2000$  °/s for the gyroscopes). The selected IMU measurement set in this study was configured to provide duplicate information for all measured wheelchair kinematics, to allow for higher accuracy and robustness of developed algorithms.

Marker positions were recorded with a 120 Hz, 24 infrared camera 3D motion capture system (Flex 13 Optitrack, Natural Point), serving as 'gold standard'. To enhance visibility range and to prevent disturbing reflections, battery powered infrared light emitting diodes markers were used instead of standard retro reflective markers. The markers were mounted on the wheelchair frame (two on the bumper bar and one on a rod at the front of the frame, see Figure 2.1). IMU units and optical motion analysis were synchronized by hardwiring all IMU sensors to a pulse generator.

### *Participants*

Differently skilled participants were recruited to test the system over a wide performance range, with 6 elite wheelchair basketball athletes, 3 players of second division teams and 11 participants without extensive wheelchair experience. Wheelchair athletes were allowed to use their custom supports and straps. Prior to the test, participants received written instructions and viewed an example video of the agility track. The study was approved by the ethical committee of the faculty of Human Movement Sciences (ECB-2014-2). All participants

signed an informed consent after being informed on the aims and procedures of the experiment.

### *Agility track*

Participants performed an agility track consisting of 21 tests covering key aspects of wheelchair basketball (track lay-out in Figure 2.2). To allow for comparison, certain tests were similar to ones used in prior research (de Groot et al., 2003; Pansiot et al., 2011), but some slightly modified to meet the capture volume dimensions. Others were designed based on consultation with wheelchair basketball experts to ensure inclusion of all critical kinematic patterns. This resulted in more vigorous tests combining bi-directional translations and rotations. To differentiate between the reliability at different performance speeds, most tests were performed at normal and high speed. The tests were performed in a motion lab with a linoleum flooring.



Figure 2.1: Celeritas 300 wheelchair used in the experiment. Dots indicate the position of the IR-LED markers (one on a rod). Arrows point at the locations of the x-IMU sensors. Orthogonal axes indicate x-IMU orientation at starting position for all x-IMU's, with the dashed arrows indicating the slightly rotated orientation of the wheel xIMUs due to the wheel camber angle. Mind the effect of wheel rotation around the Y-axis on x-IMU orientation.

**Table 2.1:**

Subject characteristics (mean and standard deviation)

non WBB = Non-Wheelchair basketball players

Elite WBB = Premier league Wheelchair basketball players.

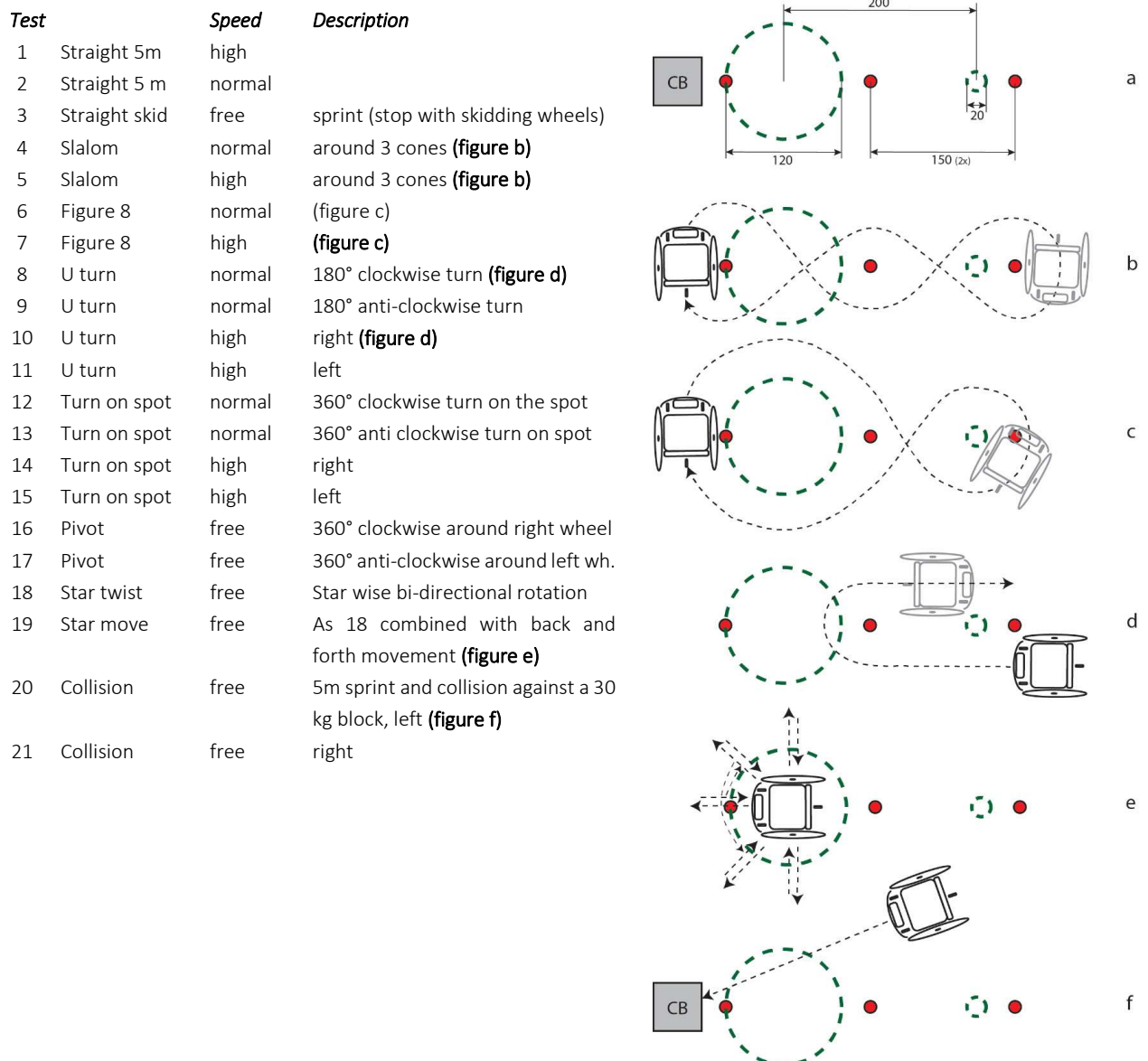
Am WBB = Second division Wheelchair basketball players

Play hist. = Mean years of playing in WBB competition.

Class = Mean players competition classification (handicap score).

<i>Subjects</i>	<i>N</i>	<i>Age</i>	<i>Sex (m/f)</i>	<i>Weight (kg)</i>	<i>Height (cm)</i>	<i>Play hist.</i>	<i>Class</i>
non WBB	11	25 (5.7)	10/1	76.7 (8.6)	181.0 (9.2)		
Elite WBB	6	25 (6.7)	5/1	69.5 (15.7)	175.8 (16.0)	6.6 (5.8)	3.7 (1.0)
Am WBB	3	31 (9.2)	2/1	84.0 (29.1)	175.8 (16.0)	1.8 (0.7)	3.6 (0.2)
total	20	26 (6.6)	17/3	75.7 (14.7)	178.1 (13.6)		

**Figure 2.2:** Track lay-out with dimensions (cm), with marks and collision block (CB; removed during other test parts).



## *Data analysis*

### **Optical motion analysis**

Optitrack 3D position data of the frame markers were acquired in Motive 1.5.1 (NaturalPoint), converted to a C3D format and imported in Matlab 2013a (Mathworks, Natick, Massachusetts, U.S.A.). Data gaps of less than 0.1s were interpolated using a cubic spline and data were filtered with a low pass filter (2<sup>nd</sup> order, Butterworth) for noise removal. Since the tests involve high speeds, a higher cut-off frequency of 10 Hz was used compared to the suggested 6 Hz (Cooper, DiGiovine, Boninger, & Shimada, 2002). A local coordinate system for the frame was calculated based on three frame marker coordinates. Using a probe, the centre of the frame and the location of floor contact of each wheel were defined as virtual markers in the frame local coordinate system. By repeated probing of the ground base markers, spatial probing accuracy was determined at  $\pm 2$  mm.

Global virtual marker coordinates were re-calculated based on frame marker coordinates and its local coordinate system, providing basis for calculation of displacement and rotation and the derived speed and rotational speed. The Instantaneous Rotation Centre (IRC) was calculated using the Reuleaux method (Reuleaux, 1875). In the analysis, IRC values were defined as the distance between the IRC and frame centre, with positive IRC values indicating a left turn. IRCs were only included for analysis if less than 5m and if rotational speed exceeded 30 °/s.

### **Inertial Measurement Unit**

Based on the start and end sync marker, IMU data were cropped and down sampled to the 120 Hz optical motion analysis sample frequency.

### *Frame displacement & speed*

Wheel acceleration signals (WhA) were used as inclination values to calculate angular orientation (AngWhA [°]) by taking the arc tangents of the two perpendicular acceleration signals in the plane of the wheel. Quadrant oriented wheel angles were converted to cumulative rotation (Matlab, unwrap).

$$\text{AngWhA} = \tan^{-1} \left( \frac{WhA_x}{WhA_z} \right) \times \left( \frac{180}{\pi} \right) [^\circ] \quad (1)$$

Wheel gyroscope (WhG) signal for measuring wheel angular speed was affected by wheelchair frame rotations as well, due to the camber angle of the wheels in sports wheelchairs. Horizontal rotations of the frame were partially measured by the wheel gyro parallel to the wheel axis, thus deforming the signal. The measured frame rotation (FrG<sub>z</sub> from the frame IMU) was used to correct the wheel gyroscope signal for these frame rotations (Pansiot et al., 2011).



The corrected gyro signal ( $WhG_c$  [°/s]) of the wheel sensors provided angular speed of the wheels and integration gave angular rotation.

$$WhG_c = WhG_y \pm \sin(\alpha_{camber}) * FrG_z \text{ [°/s]} \quad (2)$$

Combined use of wheel IMU acceleration and gyro data incorporated the stability of the acceleration (inclination) signal and the sensitivity of the corrected gyro signal into the used algorithm for wheel rotation (and derivatives). To combine those properties in a wheel rotational speed estimation ( $WhAG$  [°/s]), a complementary filter was used (Mahony, Hamel, & Pflimlin, 2005) adding the low pass filtered first *derivative* of acceleration-based wheel rotation ( $AngWhA$  [°]) data and corrected high pass filtered wheel gyro data ( $WhG_c$  [°/s]). Rotational speed times the wheel circumference ( $WC$  [m]) divided by  $360^\circ$  resulted in speed and derived displacement.

Duplicate sensor information was used to minimize the effect of skidding. The right ( $R$ )  $WhAG$  [°/s], combined with  $WC$  [m], frame horizontal rotation speed ( $FrG_z$  [°/s]) and the wheel base ( $WB$  [m]) provided an estimation of frame centre speed ( $FrC_R$  [m/s]) as illustrated in Figure 2.3. In the same way an estimation of frame centre speed was derived from the left wheel rotation speed.

$$FrC = diff\left(\frac{WhAG * \frac{WC}{360}}{f_s} \pm \left(\tan\left(\frac{FrG_z}{f_s}\right) * \frac{WB}{2}\right) * f_s\right) \left[\frac{m}{s}\right] \quad (3)$$

These two independent estimates ( $FrC_R$  and  $FrC_L$ ) were weighted averaged (see appendix) based on the ratio between wheel rotational speed (higher speed, more weight) and wheel rotational acceleration (less acceleration, more weight), resulting in a corrected frame centre speed ( $WhAG_c$  [m/s]). Furthermore, the effect of skidding wheels was reduced by comparing the calculated *derivative* of frame speed ( $WhAG_c$  [m/s]) with the frame IMU measured forward acceleration ( $FrA_x$  [m/s<sup>2</sup>]). For the brief occasions where the difference exceeded 2.5 m/s<sup>2</sup>, frame speed and displacement estimates were replaced by derivatives of the frame sensor data.

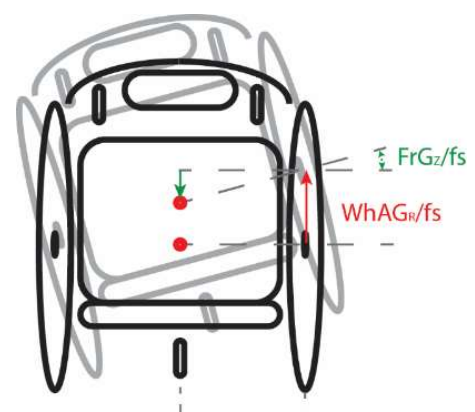


Figure 2.3: Graphical display of the frame centre displacement based on right wheel speed ( $WhAG_R$ , recalculated to displacement per frame) and correction for rotation based on frame rotation speed ( $FrG_z$ , recalculated to rotation per frame).

### Frame rotation, rotational speed & IRC

Frame rotational speed in the horizontal plane was directly measured with the frame IMU ( $FrG_z$  [ $^\circ/s$ ]) and integration of this signal provided frame rotation. The distance between the frame centre and the IRC was calculated twice, based on both right and left  $WhAG$  [ $^\circ/s$ ], combined with  $WC$  [m],  $WB$  [m] and  $FrG_z$  [ $^\circ/s$ ].

$$IRC = \left( \frac{WhAG * \frac{WC}{360}}{fs} / \frac{\pm \tan(FrG_z)}{fs} \right) \pm \frac{WB}{2} [m] \quad (4)$$

The calculated IRC was based on the weighted average of the  $IRC_R$  and  $IRC_L$  in a similar way as described for frame displacement and speed.

### *Reliability*

Reliability of the IMU method was determined by analysis of the IMU-based deviation from gold standard derived data, expressed in overall difference and RMSE values. Additionally, for relevant outcomes (speed, rotational speed and IRC) ICC between mean test averages of the IMU method and gold standard was calculated using the SPSS (IBM, SPSS 20) reliability analysis (two-way mixed single measures, absolute agreement). To identify outliers and proportional bias, Bland-Altman plots (Bland & Altman, 1986; Bland & Altman, 1995; Bland & Altman, 1999) were constructed for the same outcomes.

### Results

Study outcomes are illustrated by graphs of the results of a typical test (Figure 2.4) and a numerical summary of test results for the main or representative tests (Table 2.2).

### **Data collection summary**

During a typical measurement duration of 6 minutes, temporal differences between start and end marker in IMU storage, stayed within 5 samples ( $<0.02s$ ) and were corrected via resampling. Missing markers for optical motion analysis only occurred during 0.3% of the total measurement time, mainly during tests near the edges of the capture volume or when collision blocks obstructed line of sight (test 20 & 21).

### **Frame displacement & speed**

The introduction of more vigorous movements at high performance speeds was expected to induce skidding related errors in the results. The example plot of Figure 2.4 shows the calculated displacement and speed during a right U-turn, a test with maximal wheel skidding. After building up linear velocity, a sharp turn is launched by blocking the inside wheel. Without correction for skidding, estimates for displacement and speed deviate at the start of the turn (Figure 2.4, 173.3s), but the estimates based on duplicate sensor information (with skid correction) deviate less. This image is similar in all tests with evoked wheel skidding, both in moments of dual (brake) or single (turn) wheel skidding.

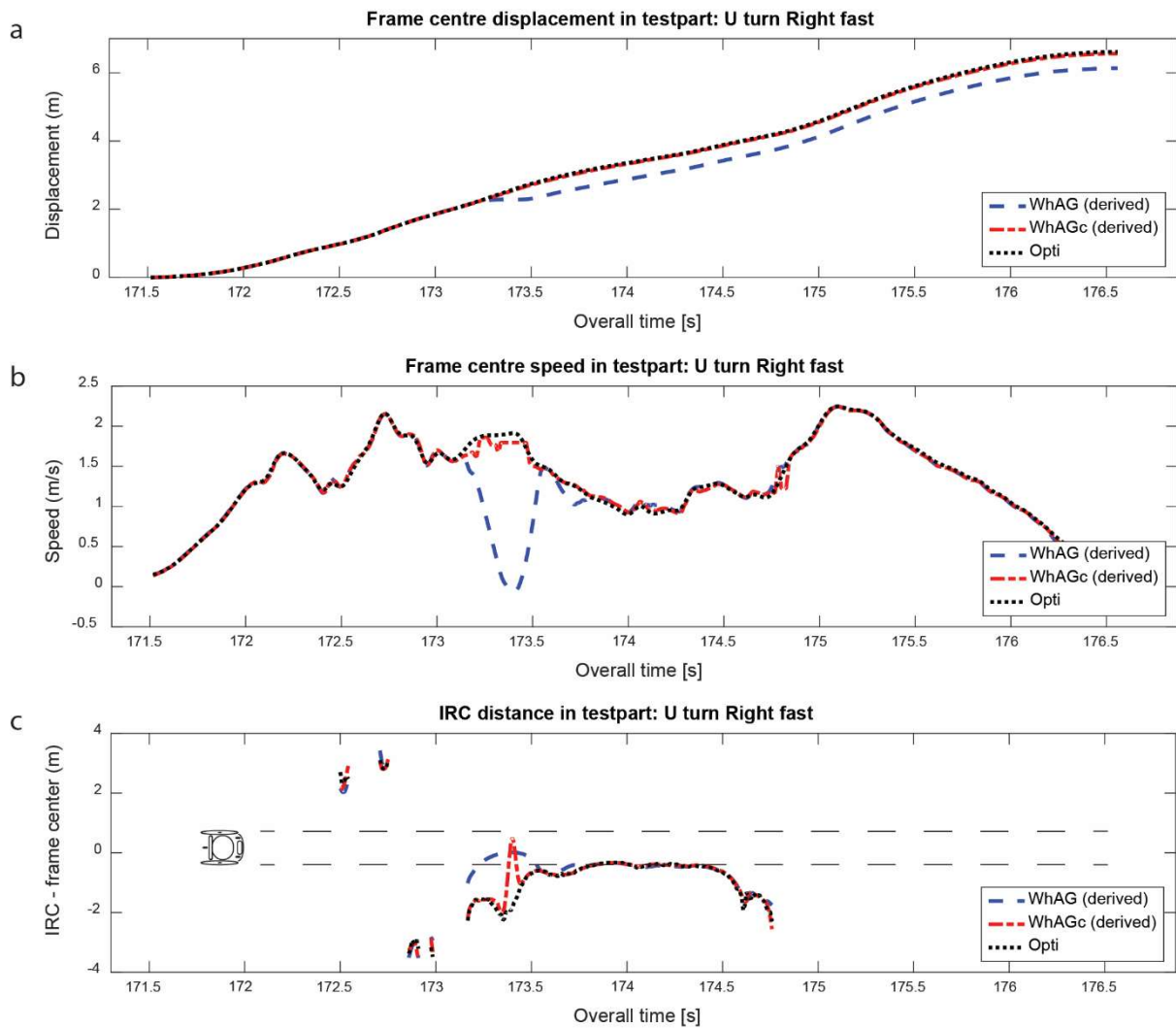


Figure 2.4: Typical example of a U-turn right; displacement (a), speed (b) and IRC (c). Note the effect of the skidding inside wheel at the start of the turn (time 173.3s) on the calculated quantities, and the positive effect of the skidding correction algorithm (WhAGc). For displacement and speed, deviations towards the Opti gold standard are hardly visible. In IRC calculations, deviations still occur, but only for very brief periods.

Displacement and average speed differences stayed below 1% for 10 tests, but increased up to 5% for 6 vigorous tests (test 3, 16, 17, 19, 20, 21, see caption Figure 2.2). Displacement RMSE values typically stayed below 0.05m except for the provocative test with intended skidding (“collision” and “star move”, see Table 2.2). Similar patterns came about for speed with RMSE values well below 0.1 m/s (except “collisions” and “straight skid”). Reliability analysis of the average test speed showed all ICC values well above 0.90 (except “collision right” ICC=0.889) and even all over 0.990 for tests performed at normal speed (Table 2.2). The error increase associated with higher performance speed, is also shown in the example Bland-Altman plot for speed during a right U-Turn (Figure 2.5a), with larger limits of agreement once a test is performed at maximum speed.

### **Frame rotation & rotational speed**

Results for frame rotation and rotational speed were directly derived from the FrGz signal. Both IMU rotation and rotational speed data showed only small deviations compared to the gold standard (RMSE  $<3^\circ$  and  $7^\circ/\text{s}$  respectively) which were stable over all tests and performance speeds (Table 2.2). For average rotational speed ICC values stayed above 0.990, with no differences between performance speeds. Limits of agreement are nearly equal for all performance speeds, as shown in the example Bland-Altman plot (Figure 2.5b). Bland-Altman plots of different tests show similar patterns, with no effect of performance speed.

### **Instantaneous Rotation Centre**

Once corrected for skidding wheels (see example of Figure 2.4c), IMU based IRC calculations demonstrate a close match with the optical motion analysis data, with short deviation jumps due to the use of thresholds in the algorithm. Numerical analysis showed small differences (RMSE  $\leq 0.05\text{m}$ ) for tests performed at normal speeds and maximal differences at high speeds (RMSE  $<0.19\text{m}$ ). The ICC values for average IRC all stayed above 0.90 except the left pivot (ICC= 0.843). For the tests with low movement speeds (“turn on the spot” and “pivot”), limits of agreement for calculated IRCs are similar for all performance speeds. In test with higher movement speed (e.g. “slalom” and “U-turn”), IRC estimation errors increase with performance speed and tend to underestimate IRC (negative mean error, see Figure 2.5c).

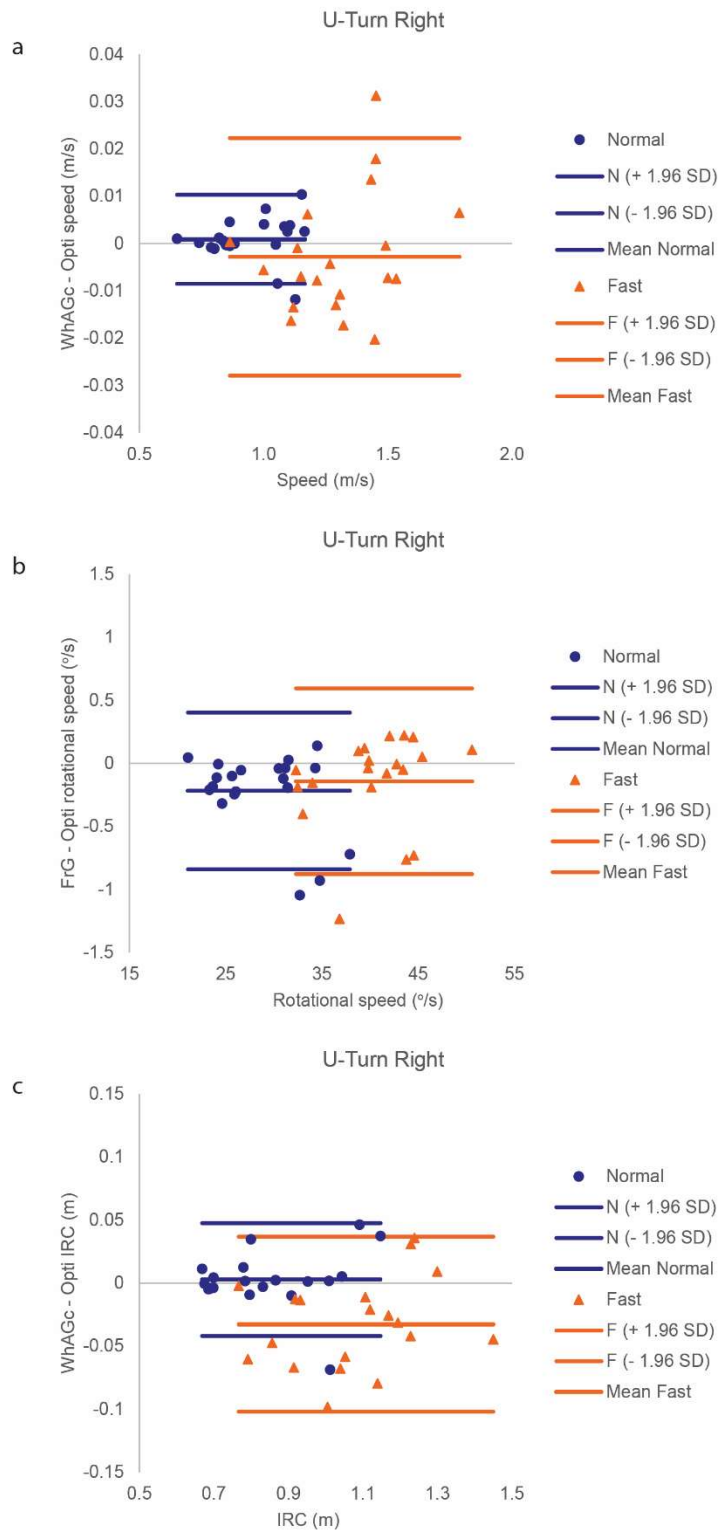


Figure 2.5: Bland-Altman plots of the U-turn right at normal (blue) and high (orange) speed. Data are plotted for speed (a), rotational speed (b) and IRC (c).

Table 2.2: Calculated average displacement, speed, rotation, rotational speed and IRC during typical tests performed at normal and high speed for optical motion analysis (Opti) and IMU (WhAGc). For all outcomes the absolute difference averaged over the 20 measurements is calculated as well as the RMSE. For mean speed, rotational speed and IRC values also the ICC is displayed.

	Speed	Displacement (m)				Speed (m/s)						
		Opti	WhAGc	difference	RMSE	Opti	WhAGc	difference	RMSE	ICC		
Straight	Normal	5.07	5.07	0.00	0.7%	0.02	0.97	0.97	0.00	0.7%	0.03	0.998
	High	4.99	4.98	-0.01	0.7%	0.02	1.75	1.75	0.00	0.8%	0.09	0.997
Slalom	Normal	10.85	10.88	0.03	0.4%	0.03	0.87	0.88	0.00	0.4%	0.02	1.000
	High	10.54	10.51	-0.03	0.4%	0.03	1.15	1.15	0.00	0.4%	0.05	1.000
Figure 8	Normal	10.32	10.31	-0.01	0.2%	0.02	0.92	0.92	0.00	0.2%	0.02	0.999
	High	10.15	10.09	-0.05	0.6%	0.04	1.25	1.25	-0.01	0.6%	0.05	0.999
U-Turn Right	Normal	6.96	6.97	0.01	0.3%	0.02	0.95	0.95	0.00	0.3%	0.02	0.999
	High	6.82	6.80	-0.02	0.8%	0.03	1.31	1.30	0.00	0.8%	0.07	0.998
Turn on spot Right	Normal	0.35	0.38	0.02		0.03	0.10	0.11	0.01		0.03	0.989
	High	0.56	0.58	0.02		0.02	0.23	0.24	0.01		0.06	0.987
Star Twist	High	1.19	1.18	-0.01		0.03	0.13	0.13	0.00		0.04	0.997
Star Move	High	6.27	6.35	0.08	1.9%	0.10	0.40	0.41	0.01		0.08	0.993
Collision Right	High	3.28	3.46	0.17	5.3%	0.07	1.26	1.33	0.07	5.3%	0.27	0.936
Straight Skid	High	4.96	4.93	-0.03	2.4%	0.04	1.54	1.53	-0.01	2.4%	0.21	0.971

	Speed	Rotation (°)				Rotational speed (°/s)					IRC distance (m)							
		Opti	FrG	difference	RMSE	Opti	FrG	difference	RMSE	ICC	Opti	WhAGc	difference	RMSE	ICC			
Slalom	Normal	797	798	0.95	0.6%	1.9	64.1	64.2	0.04	0.6%	4.48	0.999	0.75	0.75	-0.01	1.3%	0.08	0.988
	High	763	764	1.15	0.7%	1.8	82.9	82.9	0.06	0.6%	5.62	0.998	0.84	0.83	-0.02	2.3%	0.13	0.958
Figure 8	Normal	599	600	0.87	0.6%	1.2	53.2	53.2	0.05	0.6%	4.12	0.998	0.96	0.95	-0.01	1.5%	0.10	0.983
	High	588	589	0.85	0.6%	1.3	72.3	72.4	0.05	0.6%	5.33	0.998	1.04	1.02	-0.02	2.2%	0.14	0.945
U-Turn Right	Normal	212	211	-1.35	0.7%	1.1	28.9	28.6	-0.22	0.8%	3.11	0.997	0.85	0.85	0.00	1.4%	0.08	0.988
	High	213	212	-0.65	0.6%	1.2	40.5	40.4	-0.14	0.6%	4.26	0.997	1.11	1.08	-0.03	3.7%	0.19	0.973
Turn on spot Right	Normal	363	364	0.99	0.7%	1.5	102.6	102.6	0.01	0.6%	4.67	0.999	0.07	0.06			0.05	0.917
	High	368	369	0.98	0.7%	2.6	154.8	154.7	-0.09	0.5%	6.80	0.998	0.11	0.11			0.03	0.974
Star Twist	High	642	644	1.59	0.7%	1.7	84.9	85.0	0.14	0.6%	5.79	1.000	0.11	0.09			0.08	0.979
Star Move	High	610	610	-0.48	0.5%	1.4	40.7	40.7	-0.02	0.5%	3.97	1.000	0.28	0.28			0.10	0.986

## Discussion

The easy to use three IMU configuration, combined with the developed skidding algorithms showed to be reliable for measuring wheelchair kinematics. Results indicate that in most match like conditions this method with skid correction algorithms, offers reliable wheelchair kinematic data with low RMSE values and high correlations (ICC) to gold standard outcomes.

As expected, skidding wheels were the main source of error in calculating wheelchair kinematics based on IMU outcomes. In tests with evoked wheel skidding, most of the errors were effectively reduced via the use of duplicate sensory information, reducing RMSE values up to only 12% of the non-corrected RMSE values. Still, in tests at higher speeds and of a more vigorous nature, RMSE values turned out to be considerable higher than tests at normal speed. During collisions or a skidding stop, speed RMSE values reached up to 0.27 m/s, where in all other tests RMSE values stayed well below 0.1 m/s. The IRC calculation was most effected by skidding combined with algorithm thresholds (and consequent signal jumps), resulting in somewhat higher RMSE values. In all cases however, due to the short nature of skidding, this only temporarily effected RMSE between the IMU outcomes and gold standard, but had hardly any effect on the overall mean values. Therefore, the calculated ICCs over these means for speed, rotational speed and IRC, nearly all stayed above 0.90, except speed in the right collision (ICC = 0.89) and pivot left (ICC = 0.84). Increased performance speed effected limits of agreement for calculated speed (larger errors) and IRC (larger errors and underestimation), but not rotational speed. The Bland-Altman plots of rotational speed show 3 outliers in the example of the right U-turn (Figure 2.5b), but these are also present in all other plots (see supplementary website material). These outliers are based on measurements performed on the same day and are presumably due to small misalignment of the frame IMU, since one of the participants collided with the sensor with his foot. If not misaligned, RMSEs are expected to be even lower and ICCs even higher.

The IMU configuration was tested for reliability in match like conditions, yet once applied in match measurements, some limitations must be acknowledged. Rotational speeds are not restricted an expected to be comparable to match conditions, while linear top speeds were somewhat reduced due to the limited capture volume. All measurements were performed with one wheelchair with well-defined dimensions. Application of the method on different wheelchairs requires accurate measurement of their dimensions, since errors (e.g. in wheel diameter and track width) will affect the calculated kinematic outcomes proportionally.

Next to IMU system performance, overall results were influenced by study design and settings. All tests were manually selected from the complete dataset of a participant, possibly effecting RMSEs for displacement and rotation. The cut off frequency of the WhAG complementary filter was optimized for best overall results (0.05 Hz), but appeared not to be very critical within the range of 0.01-1 Hz. Thresholds for skidding correction were set to 2.5 m/s<sup>2</sup>, yet again within a wide range (1.5 – 8 m/s<sup>2</sup>) of settings, similar results were achieved.

The gold standard used was a low-cost motion capture system with reported slightly lower accuracy compared to high end systems. Typical accuracy of the Optitrack system is  $\pm 0.10$  mm ([www.naturalpoint.com](http://www.naturalpoint.com)), but in the extended measurement volume used (6x4x1m), measured errors using a 0.5m wand reached up to 0.25 mm. Although Thewlis et al. (2013) concluded that the system is well suitable for research purposes, compared to high end camera systems more variance in the gold standard is expected, especially in derivatives. Therefore, reliability analysis is narrowed to displacement and speed, since for acceleration the system is not considered a gold standard.

Using additional IMU signal information, an extra frame sensor and a skid correction algorithm, better results were achieved compared to prior research utilizing IMUs for measuring ADL wheelchair kinematics. Pansiot (2011) reported an average displacement difference of 0.095m during the figure eight test, whereas our results show only 0.008m difference on average. Even at high performance speeds, average differences did not exceed 0.052m.

The developed method proved to be reliable for collecting kinematic wheelchair data. Wheelchairs can easily be equipped with cheap lightweight IMU sensors, allowing for future research into a more detailed profile of wheelchair kinematics during a match. Combined with measurement of additional quantities, such as exerted force or observed game performance information (de Witte, submitted 2014), this allows for composition of an athlete specific performance profile. Such a profile could be used to determine the effect of sport specific training or wheelchair setting adjustment.

Conflict of interest statement

None.

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Appendix A

**Reuleaux:** Two markers ( $A^1$  and  $B^1$ ) on the wheelchair frame were defined in the horizontal plane in the first and rotated position ( $A^2$  and  $B^2$ ). Line A runs from  $A^1$  to  $A^2$ , line B runs from  $B^1$  to  $B^2$ . To find the equation of both perpendicular bisectors ( $y = dx + e$ ), the slope ( $d_a$ ) of the line perpendicular to line A was calculated as:

$$d_a = -\frac{A_x^2 - A_x^1}{A_y^2 - A_y^1} \quad (1)$$

To find e in the equation for both perpendicular bisectors the coordinates of the midpoint ( $M_a$ ) of line A was calculated as:



$$M_{a(x,y)} = A_x^1 + \frac{1}{2}(A_x^2 - A_x^1), A_y^1 + \frac{1}{2}(A_y^2 - A_y^1) \quad (2)$$

Substituting  $M_{a(x,y)}$  in the  $y = dx+e$  equation yields  $e_a$  for the line perpendicular on line A:

$$e_a = M_{a y} - d_a * M_{a x} \quad (3)$$

For line B:  $d_b$ ,  $M_{b(x,y)}$  and  $e_b$  were calculated in a similar way. The x coordinate of the IRC (the intersection of the two perpendicular bisectors) can now be calculated as:

$$IRC_x = \frac{e_b - e_a}{d_a - d_b} \quad (4)$$

Substituting  $IRC_x$  in the  $y = dx + e$  equation (for either one of the two perpendicular bisectors) yields  $IRC_y$ :

$$IRC_y = d_a * IRC_x + e_a \quad (5)$$

**Weighting for skid correction:** The frame centre speed is calculated based on the weighted average of the individual wheel rotation speed and acceleration. The speed factor per wheel is proportional to the speed ratio between right and left wheel rotation speeds:

$$SpeedFactor_R = \frac{WhAG_R}{(WhAG_R + WhAG_L)} \quad (6)$$

The acceleration factor per wheel is inversely proportional to the wheel rotation accelerations ratio:

$$AccFactor_R = \frac{diff(WhAG_L)}{diff(WhAG_R + WhAG_L)} \quad (7)$$

The overall factor is the ratio between the factor multiplications:

$$Factor_R = \frac{SpeedFactor_R * AccFactor_R}{(SpeedFactor_R * AccFactor_R) + ((1 - SpeedFactor_R) * (1 - AccFactor_R))} \quad (8)$$

The frame centre speed ( $FrC$  [m/s]) is the factor based weighted average of the two frame centre estimations based on both wheel rotation speeds:

$$FrC = (FrC_R * Factor_R) + (FrC_L * (1 - Factor_R)) \quad (9)$$

## Appendix B

Supplementary data associated with this article can be found in the online version at doi: <http://dx.doi.org/10.1016/j.jbiomech.2015.06.001>.



# Chapter 3

## Wheel skid correction

Wheel skid correction is a prerequisite to reliably measure wheelchair sports kinematics based on inertial sensors. *Procedia Engineering*





## Chapter 3: Wheel skid correction

**Wheel skid correction is a prerequisite to reliably measure wheelchair sports kinematics based on inertial sensors.**

Van der Slikke, R. M. A., Berger, M. A. M., Bregman, D. J. J., & Veeger, H. E. J.

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### Abstract

Accurate knowledge of wheelchair kinematics during a match could be a significant factor in performance improvement in wheelchair basketball. To date, systems for measuring wheelchair kinematics are not suitable for match applications or lack detail in key kinematic outcomes. This study describes the construction of wheel skid correction algorithms when using a three-inertial measurement unit (IMUs) configuration for estimating wheelchair kinematics. The reliability of the skid corrected outcomes was assessed in wheelchair basketball match-like conditions. Twenty participants performed a series of tests reflecting different motion aspects of wheelchair basketball. IMU based estimations were compared to the outcomes of a 24-camera optical motion analysis system serving as gold standard. Once the skid correction algorithms were applied, estimation errors were reduced up to 4% of their original magnitude. Calculated Root Mean Square Errors (RMSE) showed good estimates for frame displacement ( $RMSE \leq 0.05m$ ) and speed ( $RMSE \leq 0.1m/s$ ) except for three truly vigorous tests. Estimates of horizontal frame rotation ( $RMSE < 3^\circ$ ) and rotational speed ( $RMSE < 7^\circ/s$ ) were very accurate in all conditions. Differences in calculated instantaneous rotation centres (IRC) were small, but somewhat larger in tests performed at high speed (RMSE up to 0.19m). Average test outcomes for linear speed (ICCs > 0.90), rotational speed (ICC > 0.99) and IRC (ICC > 0.90) showed high correlations between IMU data and gold standard. Results indicate that wheel skid correction is a prerequisite to reliably measure wheelchair kinematics in sports conditions. Once applied, this method using cheap and affordable sensors, might enable prospective research in wheelchair basketball match conditions and contribute to individual support of athletes in everyday sports practice.

**Keywords:** *Wheelchair kinematics; Wheelchair Basketball; Reliability; Inertial Measurement Unit; Instrumented wheelchair*

## Introduction & Objectives

Increased professionalism in wheelchair basketball has raised the need for scientific input into optimizing performance. Knowledge of wheelchair kinematics during a match is prerequisite for this performance improvement (Mason et al., 2013). Unfortunately, no measurement system providing key kinematic outcomes proved reliable in competition yet. A method for measurement of wheelchair kinematics in match play would allow for applied research into athlete-wheelchair interaction by determining the relation between wheelchair settings, kinematics and performance. That knowledge could provide basis for more precise and faster optimization of individual wheelchair settings and thereby support existing experience-based expertise.

Research on the effect of wheelchair settings and propulsion techniques, on wheeling performance is available, however, data were mainly obtained with able-bodied individuals in artificial circumstances and hardly ever sport specific. The effect of propulsion techniques (van der Woude et al., 1998), seat height (Masse et al., 1992) and axle position (Boninger et al., 2000) on performance during normal wheeling is well investigated. The apparent subsequent step in research is the introduction of ambulatory methods, measuring individual sports performance in an easy and affordable manner.

Ambulatory measurement systems, like inertial measurement units (IMU's) mounted on a wheelchair, proved reliable for quantifying wheelchair activity in normal daily-life conditions, with good estimates of distance covered, average speed and duration of movement (Coulter et al., 2011; Sonenblum et al., 2012). Pansiot (Pansiot et al., 2011) tested the performance of gyro/accelerometers in both rear wheelchair wheels during a lab-based figure 8 trajectory test. The system proved reliable in estimating velocity, heading, distance covered and motion trajectory. On using inertial sensors during wheelchair sports events only a limited number of studies were conducted. Hiremath (Hiremath, Ding, & Cooper, 2013) compared their outcomes of a gyroscope on the spokes with several other systems (tape measures, smart wheel and a motion capture system) and found an overall accuracy above 95%. Rhodes (Rhodes et al., 2014) found a good reliability of iGPS position estimation in wheelchair rugby, but poor sampling frequency ranges reduced application for calculation of other kinematics.

A reliable, robust and easily applicable system to measure wheelchair kinematics during wheelchair basketball matches is not available yet. The use of IMUs enables cheap and user-friendly measurements, but the reliability of such a method is highly dependent on the algorithms used to process the sensor output. This study describes the basis for an algorithm to significantly reduce errors in IMU based estimation of wheelchair kinematics. To assess the reliability, kinematics like displacement, speed, rotation (speed) and curvature of the path were compared to outcomes of a 3D optical motion analysis system.

## Methods

### Setup and participants

Twenty participants (Table 3.1) performed a series of 21 tests reflecting different motion aspects of wheelchair basketball, such as a straight 5m sprint; a slalom; a U-turn; moving back and forth while rotating; collide and spin (see Figure 3.1). During these tests wheelchair kinematics were simultaneously measured using IMUs on wheels and frame, and a 24-camera optical motion analysis system serving as gold standard. Wheelchair kinematics like frame displacement, speed and rotation based on IMU outcomes were compared to gold standard outcomes, to test the reliability of the IMU sensor configuration.

Table 3.1: Subject characteristics (mean and standard deviation), with Non Wheelchair basketball players (non WBB), Premier league Wheelchair basketball players (Elite WBB), Second division (amateur) Wheelchair basketball players (Am WBB), Mean years of playing in WBB competition (Play hist.) and Competition Classification (Class).

Subjects	N	Age	Sex (m/f)	Weight (kg)	Height (cm)	Play hist.	Class
non WBB	11	25 (5,7)	10/1	76,7 (8,6)	181,0 (9,2)		
Elite WBB	6	25 (6,7)	5/1	69,5 (15,7)	175,8 (16,0)	6,6 (5,8)	3,7 (1,0)
Am WBB	3	31 (9,2)	2/1	84,0 (29,1)	175,8 (16,0)	1,8 (0,7)	3,6 (0,2)
Total	20	26 (6,6)	17/3	75,7 (14,7)	178,1 (13,6)		

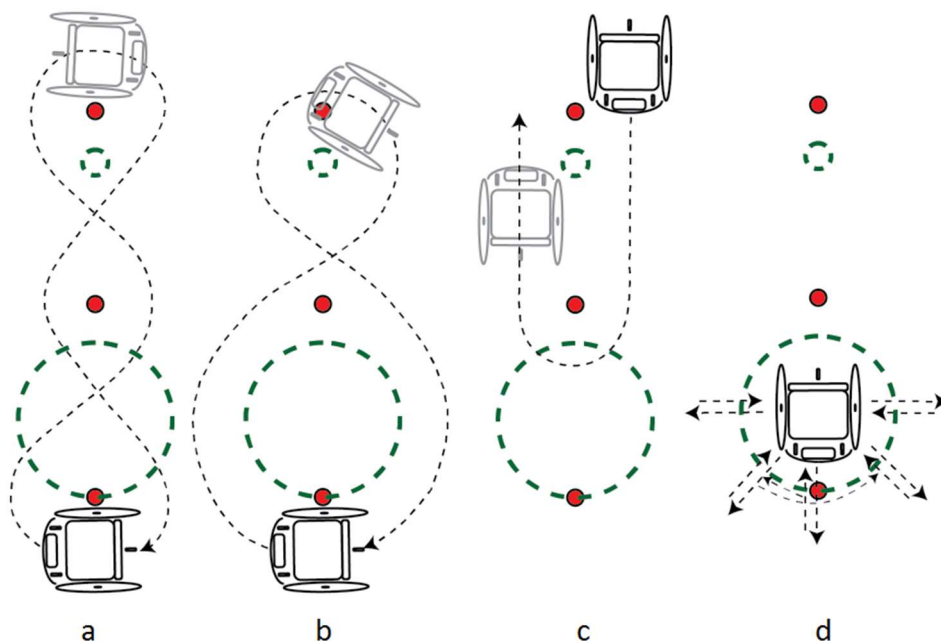


Figure 3.1: Test track layout and example tests:

- a) Slalom test;
- b) Figure eight test;
- c) U-turn (left & right);
- d) Star twist (moving back and forth, combined with rotation).

### *Inertial Measurement Units (IMU)*

Wheelchair linear displacement, speed and curvature of the path was calculated based on rotation of the wheels, which in turn was based on the combined signal of the wheel acceleration sensor and gyroscope. After application of a correction for camber angle (Pansiot et al., 2011; van der Slikke, Berger, Bregman, Lagerberg, & Veeger, 2015) wheel rotation times wheel circumference produced displacement and derivatives. Rotation and rotational speed of the wheelchair frame in the horizontal plane were directly derived from the frame sensor gyroscope.

### *Wheel Skid Correction Algorithms*

The measurement configuration was chosen allowing for multiple ways of calculation of the same kinematics. Frame forward acceleration for example was measured directly by the frame acceleration sensor, but also calculated based on measured wheel rotation. These different sensor estimations were used to construct skid correction algorithms.

To correct for concurrent wheel skidding, low pass filtered (20Hz) forward acceleration derived from the wheels (average of left and right WhAG) was compared to the low pass filtered (20Hz) measured forward frame acceleration. For occasions with acceleration differences over  $2.5 \text{ m/s}^2$ , the corrected frame *speed* was calculated based on the frame sensor acceleration signal. This corrected frame speed signal was used for further kinematic calculations.

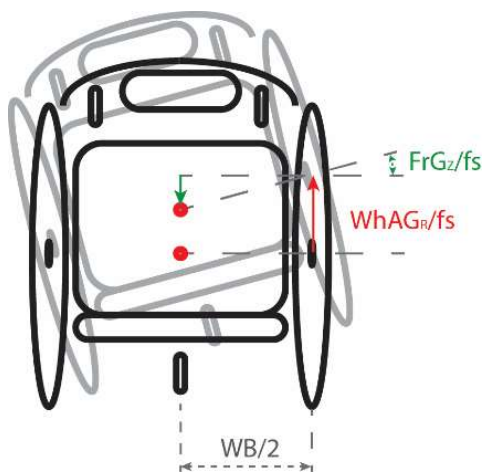


Figure 3.2: Graphical display of the frame centre displacement (red dots) based on right wheel speed (WhAGR) and correction for rotation based on frame rotation speed (FrGz) [10]



A second skid correction was developed to correct for single wheel skidding, typically occurring in a sharp turn (Figure 3.3). During turns, frame centre displacement was calculated twice, based on both wheels individually combined with the measured frame rotation. For each wheel, frame displacement was calculated as the wheel displacement (WhAG) plus or minus the tangent of the frame rotation (FrG) times half the wheelchair wheel base (WB, Figure 3.2). These two estimates were equal if both wheels are rolling, but deviated when one wheel was skidding. To assure the estimate of the least skidding wheel was used, a weighted average of the estimates was applied with less weight for the wheel with the lowest rotation speed (SpeedFactor) or highest rotational deceleration (AccFactor). Equation 1, 2 and 3 show the calculations for the right wheel-based estimations:

$$SpeedFactor_R = \frac{WhAG_R}{(WhAG_R + WhAG_L)} \quad (1)$$

$$AccFactor_R = \frac{diff(WhAG_L)}{diff(WhAG_R + WhAG_L)} \quad (2)$$

The overall factor is the ratio between the factor multiplications:

$$Factor_R = \frac{SpeedFactor_R * AccFactor_R}{(SpeedFactor_R * AccFactor_R) + ((1 - SpeedFactor_R) * (1 - AccFactor_R))} \quad (3)$$

The frame centre speed (FrC) is the factor based weighted average of the two frame centre speed estimations (left and right wheel based):

$$FrC = (FrC_R * Factor_R) + (FrC_L * (1 - Factor_R)) \quad (4)$$

### Reliability analysis

Reliability of the IMU method with and without wheel skid correction, was determined by analysis of the IMU-based deviation from gold standard derived data, expressed in overall difference and RMSE values. Additionally, for relevant outcomes (speed, rotational speed and IRC) ICC between mean test averages of the IMU method and gold standard was calculated (ICC, two-way mixed single measures, absolute agreement).

## Results

As expected, kinematics derived from wheel rotation (WhAG) showed increased errors during wheel skidding conditions. Detailed analysis of test signals showed deviations of linear displacement estimations (and derivatives) once some speed was build up and one or two wheels were blocked, resulting in a wheel skid (Figure 3.3).

Rotations and rotational speed of the frame in the horizontal plane were directly derived from the frame sensor gyroscope (FrG), thus not affected by any wheel skidding. Deviations of the IMU configuration estimations towards the gold standard are shown in Table 3.2. Calculated Root Mean Square Errors (RMSE) showed good estimates for frame displacement ( $RMSE \leq 0.05m$ ) and speed ( $RMSE \leq 0.1m/s$ ), except for three truly vigorous tests (during collisions and an evoked skidding stop). Estimates of frame rotation in the horizontal plane ( $RMSE < 3^\circ$ ) and rotational speed ( $RMSE < 7^\circ/s$ ) were very accurate in all tests.

Differences in calculated instantaneous rotation centers (IRC) were small, but somewhat larger in tests performed at high speed. At normal speed the error in calculated distance between IRC and frame centre stayed below an RMSE of 0.10 m, but at high performance speeds it reached up to an RMSE of 0.19 m. For linear speed (ICC's > 0.90), rotational speed (ICC > 0.99) and IRC (ICC > 0.90) average outcomes showed high correlations between IMU estimates and gold standard. So, even estimates with higher RMSE values, showed small errors once averaged per test.

## Discussion and Conclusion

Results indicate that in most match like conditions skid correction algorithms are needed to reliably measure wheelchair kinematics. Using skid corrections, low RMSE values and high correlations (ICC) to gold standard outcomes were found.

As expected, skidding wheels were the main source of error in calculating wheelchair displacement (and derivatives) and IRC estimations. In tests with evoked wheel skidding, most of the errors of the IMU based estimations were effectively reduced via the use of duplicate sensory information, reducing RMSE values up to 4% of the non-corrected RMSE values. Occasionally wheel skid corrections were not effective or even reduced accuracy, such as in tests performed at normal speeds or during collisions. Even after correction, in tests at higher speeds and of a truly vigorous nature, RMSE values turned out to be considerable higher than tests performed at normal speed.

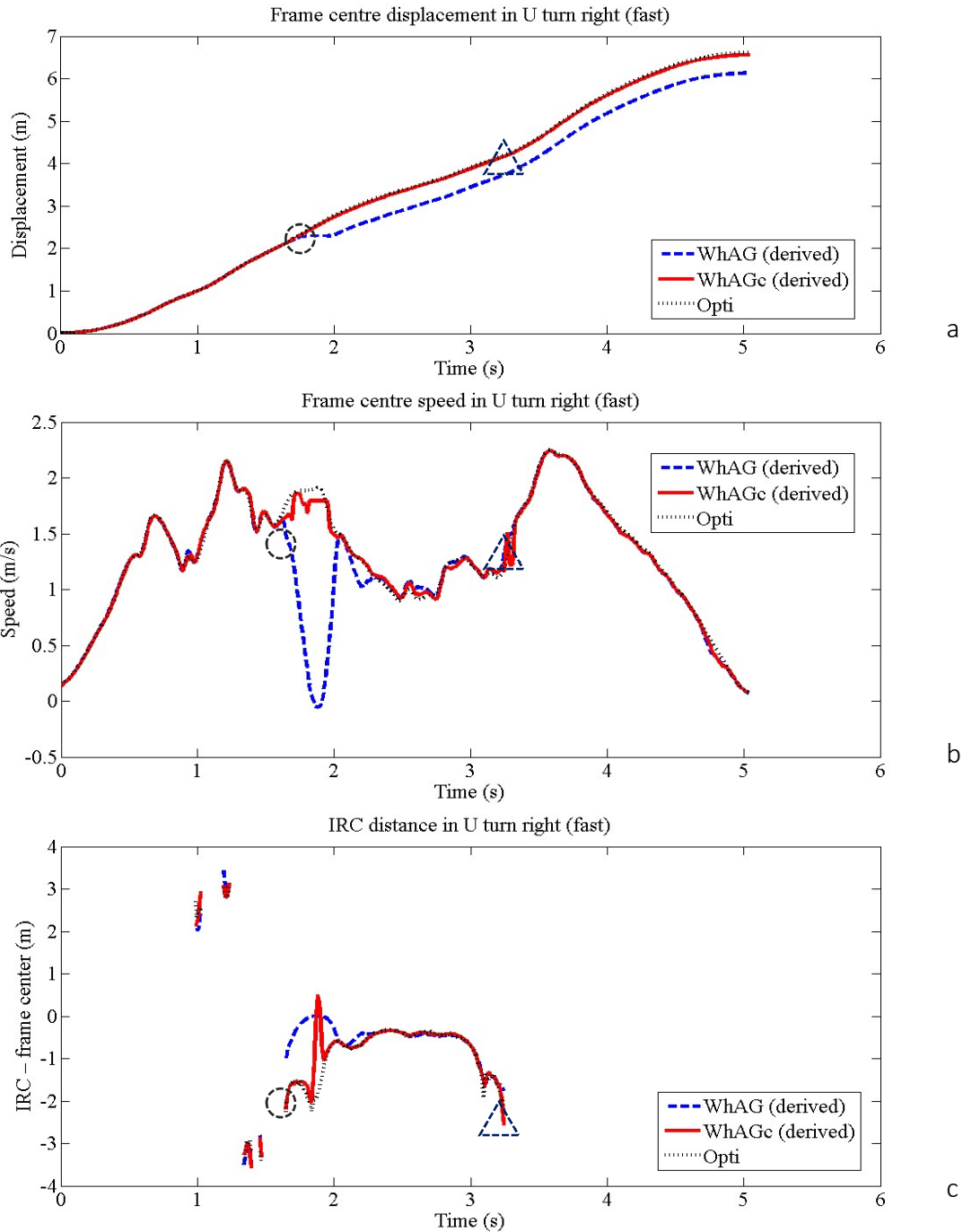


Figure 3.3: Example plot of the calculated kinematics during a right U turn performed at high speed, with (a) displacement, (b) speed and (c) distance between frame and rotation centre (IRC).

The black dotted line shows the Optitrack (Opti) gold standard outcomes, the blue dashed line the IMU calculations without skid corrections (WhAG) and the red solid line IMU outcomes with both skid corrections applied (WhAGc). The dashed O marks the start and the triangle the end of the actual turn (with 2.5m straight before and after).

Mind the deviation towards Opti at the start of the turn for the outcomes without corrections (WhAG) and the effective reduction of error due to the skid correction algorithm (WhAGc). Due to the application of a threshold for the linear skid some minor signal jumps occur (see speed and IRC plot). Positive IRC values at 1s indicate a minor left deviation, to swirl around the cone at the turning point.

Table 3.2: The RMSE values and ICCs for test means for the difference between IMU method and Optitrack gold standard, during typical tests performed at normal and high speed. Black values are the skid corrected and gray italic the non skid corrected outcomes. Tests performed at high speed are more prone to measurement errors due to wheel skidding (van der Slikke et al., 2015).

Test	Speed	Displacement		Speed (m/s)		ICC	Rotation	Rot. speed (°/s)		IRC distance (m)		
		RMSE	RMSE	RMSE	RMSE		RMSE	RMSE	ICC	RMSE	RMSE	ICC
Straight	Normal	0.02	<i>0.03</i>	0.03	<i>0.05</i>	0.998						
	High	0.02	<i>0.05</i>	0.09	<i>0.18</i>	0.997						
Slalom	Normal	0.03	<i>0.06</i>	0.02	<i>0.02</i>	1.000	1.9	4.48	0.999	0.08	<i>0.06</i>	0.988
	High	0.03	<i>0.18</i>	0.05	<i>0.14</i>	1.000	1.8	5.62	0.998	0.13	<i>0.53</i>	0.958
Figure 8	Normal	0.02	<i>0.03</i>	0.02	<i>0.02</i>	0.999	1.2	4.12	0.998	0.10	<i>0.07</i>	0.983
	High	0.04	<i>0.10</i>	0.05	<i>0.10</i>	0.999	1.3	5.33	0.998	0.14	<i>0.24</i>	0.945
U-Turn Right	Normal	0.02	<i>0.05</i>	0.02	<i>0.03</i>	0.999	1.1	3.11	0.997	0.08	<i>0.07</i>	0.988
	High	0.03	<i>0.24</i>	0.07	<i>0.24</i>	0.998	1.2	4.26	0.997	0.19	<i>0.98</i>	0.973
Turn on spot Right	Normal	0.03	<i>0.03</i>	0.03	<i>0.03</i>	0.989	1.5	4.67	0.999	0.05	<i>0.04</i>	0.917
	High	0.02	<i>0.02</i>	0.06	<i>0.06</i>	0.987	2.6	6.80	0.998	0.03	<i>0.04</i>	0.974
Star Twist	High	0.03	<i>0.04</i>	0.04	<i>0.04</i>	0.997	1.7	5.79	1.000	0.08	<i>0.21</i>	0.979
Star Move	High	0.10	<i>0.26</i>	0.08	<i>0.09</i>	0.993	1.4	3.97	1.000	0.10	<i>0.16</i>	0.986
Collision	High	0.07	<i>0.07</i>	0.27	<i>0.23</i>	0.936						
Straight	High	0.04	<i>0.18</i>	0.21	<i>0.51</i>	0.971						

The proven reliability of the developed method enables wheelchair athletes, coaches and researchers to perform ambulant measurements and applied research in the field of wheelchair sports. Wheelchairs can easily be equipped with cheap lightweight IMU sensors, providing wheelchair kinematics if wheel diameter and track width are known and skid correction is applied. In future research, the use of this method might allow for a more detailed profile of wheelchair kinematics during a match. Combined with measurement of additional quantities, such as exerted force or observed game performance information, this allows for composition of an athlete specific performance profile. Such a profile could be used to determine the effect of sport specific training or wheelchair setting adjustment.

A close-up, low-angle photograph of a wheelchair's metal frame. The frame is made of polished, reflective metal tubes. A white, rectangular sensor device with a prominent orange circular light on its top surface is mounted to the frame. The background is a bright, out-of-focus white light, creating a strong contrast with the dark metal of the wheelchair.

# Chapter 4

## Key features of wheelchair mobility performance

From big data to rich data: The key features of athlete  
wheelchair mobility performance.

*Journal of Biomechanics*



## Chapter 4: Key features of wheelchair mobility performance

### From big data to rich data: The key features of athlete wheelchair mobility performance.

Slikke, van der, R. M. A., Berger, M. A. M., Bregman, D. J. J., & Veeger, H. E. J.

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<https://doi.org/10.1016/j.jbiomech.2016.08.022>

#### Abstract

Quantitative assessment of an athlete's individual wheelchair mobility performance is one prerequisite needed to evaluate game performance, improve wheelchair settings and optimize training routines. Inertial Measurement Unit (IMU) based methods can be used to perform such quantitative assessment, providing a large number of kinematic data. The goal of this research was to reduce that large amount of data to a set of key features best describing wheelchair mobility performance in match play and present them in meaningful way for both scientists *and* athletes. To test the discriminative power, wheelchair mobility characteristics of athletes with different performance levels were compared.

The wheelchair kinematics of 29 (inter-)national level athletes were measured during a match using three inertial sensors mounted on the wheelchair. Principal component analysis was used to reduce 22 kinematic outcomes to a set of six outcomes regarding linear and rotational movement; speed and acceleration; average and best performance. In addition, it was explored whether groups of athletes with known performance differences based on their impairment classification also differed with respect to these key outcomes using univariate general linear models. For all six key outcomes classification showed to be a significant factor ( $p < 0.05$ ).

We composed a set of six key kinematic outcomes that accurately describe wheelchair mobility performance in match play. The key kinematic outcomes were displayed in an easy to interpret way, usable for athletes, coaches and scientist. This standardized representation enables comparison of different wheelchair sports regarding wheelchair mobility, but also evaluation at the level of an individual athlete. By this means, the tool could enhance further development of wheelchair sports in general.

## Introduction

Since wheelchair basketball has reached an increased level of professionalism, there is a need to optimize all factors contributing to team performance, like team interplay and individual athlete performance. The athlete's performance in turn can be sub-divided in physical performance, mobility performance and game performance. Physical performance only concerns the athlete (Bloxham et al., 2001), whereas mobility performance is the measure for the combined wheelchair-athlete combination (Mason et al., 2013). Therefore, although mobility performance is established by athlete exertion, it is often expressed in terms of wheelchair kinematics (Mason, van der Woude, Lenton, & Goosey-Tolfrey, 2012). Game performance is an overall measure and defined as the true quality of an athlete's contribution to the game (Byrnes, Hedrick, Hedrick, Byrnes, & Shaver, 1994). The present study investigated ways to improve quantification and measurement of wheelchair mobility performance characteristics, to enable evaluation of interventions aiming at optimizing wheelchair-athlete interaction.

To date, wheelchair mobility performance is mostly considered and utilized as a concept, instead of a well quantified measure. With regard to activities, mobility performance during a match can be described based using systematic observation (de Witte et al., 2016). With more focus on kinematic aspects of mobility performance, Sarro et al. (2010) used video tracking and Rhodes et al. (2015) presented an accurate iGPS system for measuring field position. Still, those systems require to (temporarily) instrument the sports hall and do not allow for calculations of higher order kinematic outcomes due to limited sample frequencies (10 and 16 Hz respectively). Spörner et al. (2009) used a miniature data logger to collect match data of both wheelchair rugby and basketball athletes and claimed to be the first to provide match data on average speed and distance. Although these systems provide data on aspects of mobility performance, they lack outcomes related to (rotational) acceleration, which is expected to be important for quantification of wheelchair performance (van der Slikke et al., 2015).

Recent technical developments allow wheelchair mobility performance to be quantified using an Inertial Measurement Unit (IMU) setup. However, this may result in an abundance of sometimes hard to interpret kinematic data. Usma et al. (2010) used IMUs to determine performance of wheelchair rugby players in a standard agility test while Fuss et al. (2012) used fractal dimension analysis of frame acceleration to identify activity patterns during wheelchair rugby match play. A newly developed method utilizing IMUs (van der Slikke et al., 2015) appeared reliable for measuring an extensive set of wheelchair kinematic outcomes, but was not yet applied in actual match play and lacked usability for sports practice given the bulk of outcomes provided.

The aim of this study was to compose an easy to interpret display of key features best representing wheelchair mobility performance. Three subsequent steps were undertaken to meet that aim: 1) reduction of a large number of kinematic outcomes to a set of key kinematic



outcomes; 2) seeking a way to display key kinematic features in a concise but clear fashion, usable for coach and athlete; 3) testing if key features discriminate well between athletes of different performance levels. Since mobility performance is known to strongly relate to classification in wheelchair rugby (Rhodes et al., 2015; Sarro et al., 2010; Usma-Alvarez et al., 2010), it should do so in wheelchair basketball as well, since both games use the same classification principle. Given this assumed performance difference due to classification, the new method was rated accurate if indeed classification appeared to be a significant factor in measured kinematic outcomes.

## Methods

### *Setup & Participants*

Wheelchair kinematics of wheelchair basketball athletes were measured during 11 premier division competition and friendly international level matches. Twenty-nine athletes were measured with twelve male first division athletes (National NLD), nine female internationals (NLD & GBR) and eight male internationals (NLD, ISR & AUS). Athlete classification was evenly distributed over these three competition level groups (Table 4.1, Appendix A). This study was approved by the ethical committee of the faculty of Human Movement Sciences: ECB-2014-2. All participants signed an informed consent after being informed on the aims and procedures of the experiment.

**Table 4.1: The distribution of classification and age (years) per competition level group.**

<i>Level group</i>		<i>Mean</i>	<i>SD</i>	Classification						
				1	1.5	2	2.5	3	4	4.5
National Male (NM)	Class	2.5	1.4	3	2	2		1	3	1
	Age	27.9	9.4							
International Male (IM)	Class	2.8	1.1	1	1	3	1	1	1	1
	Age	30	6							
International Female (IF)	Class	2.8	1.3	1	2		2	1	1	2
	Age	28.3	8.8							
<b>Total</b>				<b>5</b>	<b>5</b>	<b>5</b>	<b>3</b>	<b>3</b>	<b>5</b>	<b>4</b>

### *Inertial Measurement Units*

The athlete's wheelchair was equipped with three IMUs (X-IO technologies, Figure 4.1), one on each rear wheel axis and one on the rear frame bar. The frame sensor was used for measuring forward acceleration as well as rotation of the frame in the horizontal plane. The combined signal of wheel sensor acceleration and gyroscope was used to estimate wheel rotation, which in turn provided frame displacement given the wheel circumference.



Figure 4.1: Measurement setup, with IMUs on wheels and frame and measurements during a match. (Photograph by [www.frankvanhollebeke.be](http://www.frankvanhollebeke.be)).

Horizontal frame rotation estimates were used to correct the wheel gyroscope signal for wheel camber angle, as described by Pansiot et al. (2011), Fuss et al. (2012) and van der Slikke et al. (2015). Furthermore, a skid correction algorithm was applied to reduce the effect of single or concurrent wheel skidding (van der Slikke, Berger, Bregman, & Veeger, 2015a).

### *Analysis*

#### **Kinematic outcomes**

A total of 22 wheelchair kinematic outcomes regarding forward and rotational movement were initially extracted from the IMU based measurement method. To enable genuine comparison independent of match time, average kinematic outcomes were calculated for actual movement time ( $>0.1$  m/s) and rotation time ( $> 10$  °/s) respectively. For all movements of at least 0.5 seconds, basic kinematic outcomes were calculated: forward frame displacement, speed, acceleration, rotation in the horizontal plane, rotational speed and rotational acceleration. Additionally, combined kinematic outcomes were calculated including rotational kinematic outcomes with minimal forward speed (turn) and rotational kinematic outcomes while driving (curve). Both turn and curve kinematic outcomes were calculated with different boundaries for forward speed (FS): “turn”, FS  $-0.5 - 0.5$  m/s; “turn2”, FS  $-1.5 - 1.5$  m/s (1.5m/s equals average FS); “curve”, FS  $1 - 2$ m/s and “curve2”,  $1.5+m/s$ . For all (rotational) speed related kinematic outcomes, also averages of best ( $n=5$ ) performances were calculated (see Appendix B for a more detailed description of outcomes).

#### **Statistics**

Principal Component Analysis (PCA) was used to reduce the number of kinematic outcomes to arrive at independent key factors that describe an athlete’s wheelchair mobility performance. The Kaiser-Meyer-Olkin test was used to verify if the dataset of 22 outcomes was suitable for PCA (KMO value  $>.5$ ). The PCA was applied with a VariMax rotation to identify components that are not highly correlated. The point of inflexion in the scree-plot was used to make an initial

selection for the number of retaining components (Field, 2013). The PCA shows how well each of the 22 kinematic outcomes load ( $-1 < 1$ ) on those retaining components. For each component, one kinematic outcome was selected, typically the one with the highest loading. In case of a nearly similar loading of several outcomes on a component, also the second or third outcome could be selected based on conceptual reasons. Less complex outcomes, easier to interpret for sports application were preferred over more complex outcomes and a somewhat even distribution between outcomes describing linear or rotational kinematics was aimed at (see Appendix C for application of this concept to the results).

Univariate one-way ANOVA's (General Linear Models) were used to test whether groups of athletes with different performance levels (different classification) also differed with respect to the key outcomes that were identified using PCA. The athlete's classifications ranged from 1 – 4.5, so the overall group was split in seven classification groups (Table 4.1, no athletes classified as 3.5). A Holm-Bonferroni correction was applied to correct for multiple testing. In addition, univariate two-way ANOVA's were used to determine whether the differences in the key outcomes between the performance level groups were different for competition levels. If this interaction was not significant ( $p > 0.05$ ), results regarding performance level were considered to be independent from competition level.

## Results

### *Kinematic outcomes*

Due to high impacts in matches, there was malfunctioning of one of the three sensors in two measurements. One athlete could be measured in a subsequent match, so only the measurement of one international male athlete was lost and the kinematic outcomes of 29 athletes were used in the PCA (Table 4.1).

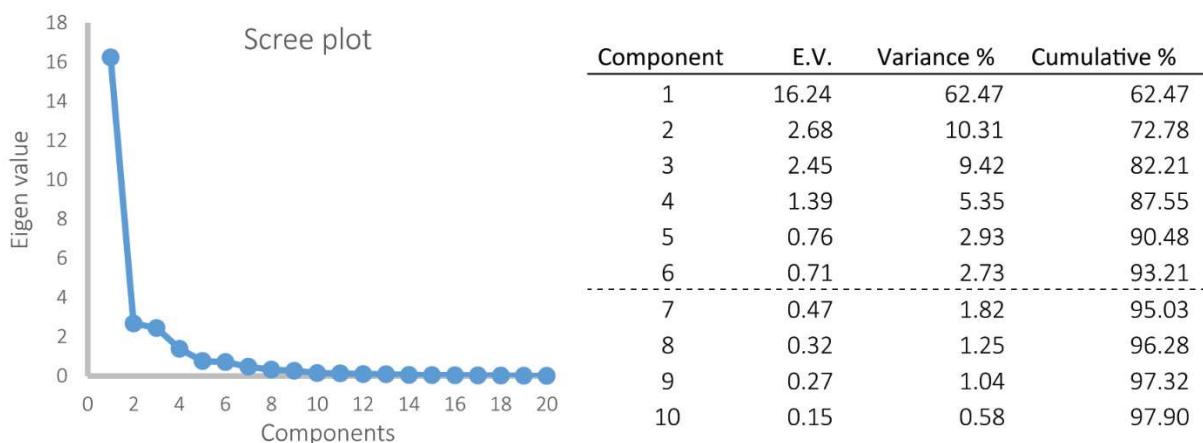


Figure 4.2: Scree plot for principal component analysis with the table on the right showing initial Eigen Values (E.V.) and explained variance for the first 10 components.

Six key kinematic outcomes were selected based on PCA, after the dataset was tested for PCA suitability by the Kaiser-Meyer-Olkin test (0.695, KMO >0.5). The PCA scree plot shows a first point of inflexion after four components and a less prominent point of inflexion after six components (Figure 4.2). For subsequent analysis, these six components were used. Table 4.2 shows the three outcomes with the highest load on each PCA component and the final selection of outcomes made. The final set of kinematic outcomes selected for the wheelchair mobility performance comprises: 1) average of the best five rotational speeds in a turn (-1.5 – 1.5m/s forward speed); 2) average rotational acceleration; 3) average forward acceleration in the first 2 meter from standstill; 4) average forward speed; 5) average rotational speed in a curve (> 1.5m/s forward speed); 6) average of five best forward speeds.

**Table 4.2:** The 22 kinematic outcomes ordered by their loading on the PCA components. For each component, the value for the three kinematic outcomes with the highest load are displayed. The outcomes are divided by direction: forward (Fo) or rotational (Ro); order: speed (Sp) or acceleration (Acc); by type: turning on the spot (Turn), turning at below average speed (Turn2), curving at average speed (Curve, 1-2 m/s) and curving at above average speed (Curve2, >1.5m/s); and finally, by average (Avg) or average of best 5 (Best) outcomes. The most right column indicates the selected kinematic outcome per component.

Outcome Number	Direction	Order	Type	Avg or Best	Component						Selection per component	
					1	2	3	4	5	6		
13	Ro	Sp	Turn2	Best	.872							1
22	Ro	Acc	60d	Best	.862							
12	Ro	Sp	Turn	Best	.829						.121	
20	Ro	Acc	Curve2	Avg		.949						
16	Ro	Acc		Avg		.923						2
19	Ro	Acc	Curve	Avg		.911						
5	Fo	Acc	2m	Best			.946					
4	Fo	Acc	2m	Avg			.829					3
2	Fo	Sp		Best			.628			.685		6
7	Ro	Sp	Turn	Avg				.720				
8	Ro	Sp	Turn2	Avg				.677				
1	Fo	Sp		Avg				.573		.113		4
10	Ro	Sp	Curve2	Avg					.744			5
9	Ro	Sp	Curve	Avg					.523			
6	Ro	Sp		Avg					.491			
3	Fo	Acc		Avg								
11	Ro	Sp		Best								
17	Ro	Acc	Turn	Avg								
18	Ro	Acc	Turn2	Avg								
14	Ro	Sp	Curve	Best								
15	Ro	Sp	Curve2	Best								
21	Ro	Acc	60d	Avg								

### Graphical display

To support the use of the new set of wheelchair mobility performance outcomes, results were displayed in a single easy to interpret radar plot with an innate axis for each outcome. The upper and lower limit per axis is set by the group average plus and minus 2.5 standard deviations. The PCA allowed for an even distribution of kinematic outcomes regarding forward or rotational movement. For each direction an average speed measure, a best speed measure and average acceleration measure was selected. The top half of the plot describes forward motion and the lower half rotational kinematic outcomes, with from left to right: average (rotational) speed, best (rotational) speed and average acceleration. If grouped by three classification groups, the wheelchair mobility performance plots look like Figure 4.3, while Figure 4.4 shows the wheelchair mobility performance if split by competition level.

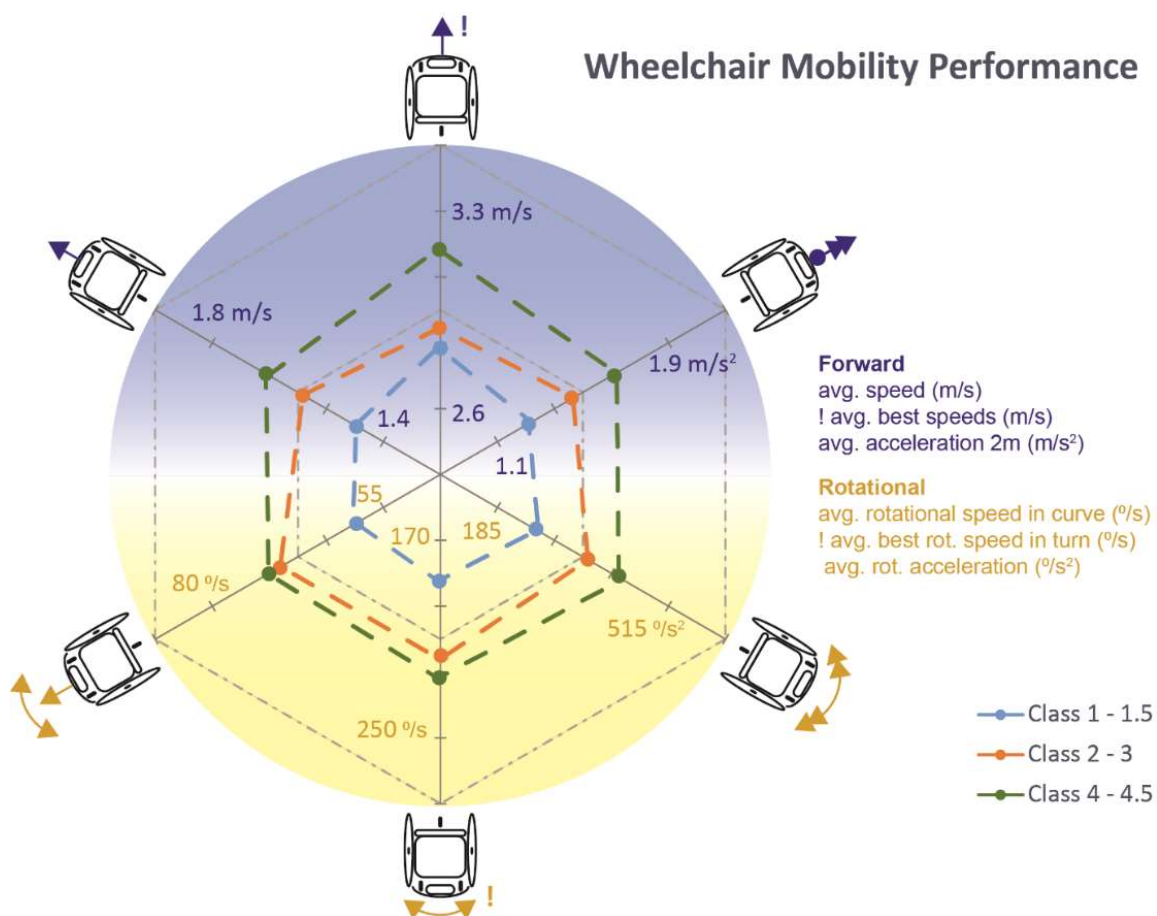


Figure 4.3: Wheelchair mobility performance plot for three classification groups. The low classified athletes (class 1 – 1.5) perform below average on all six kinematic outcomes. The high-classified athletes (class 4 – 4.5) perform best on all outcomes. The middle-classified athletes (class 2-3) perform close to the low-classified athletes regarding best forward speed (top), but close to high classified athletes regarding rotational speeds (bottom left and bottom).

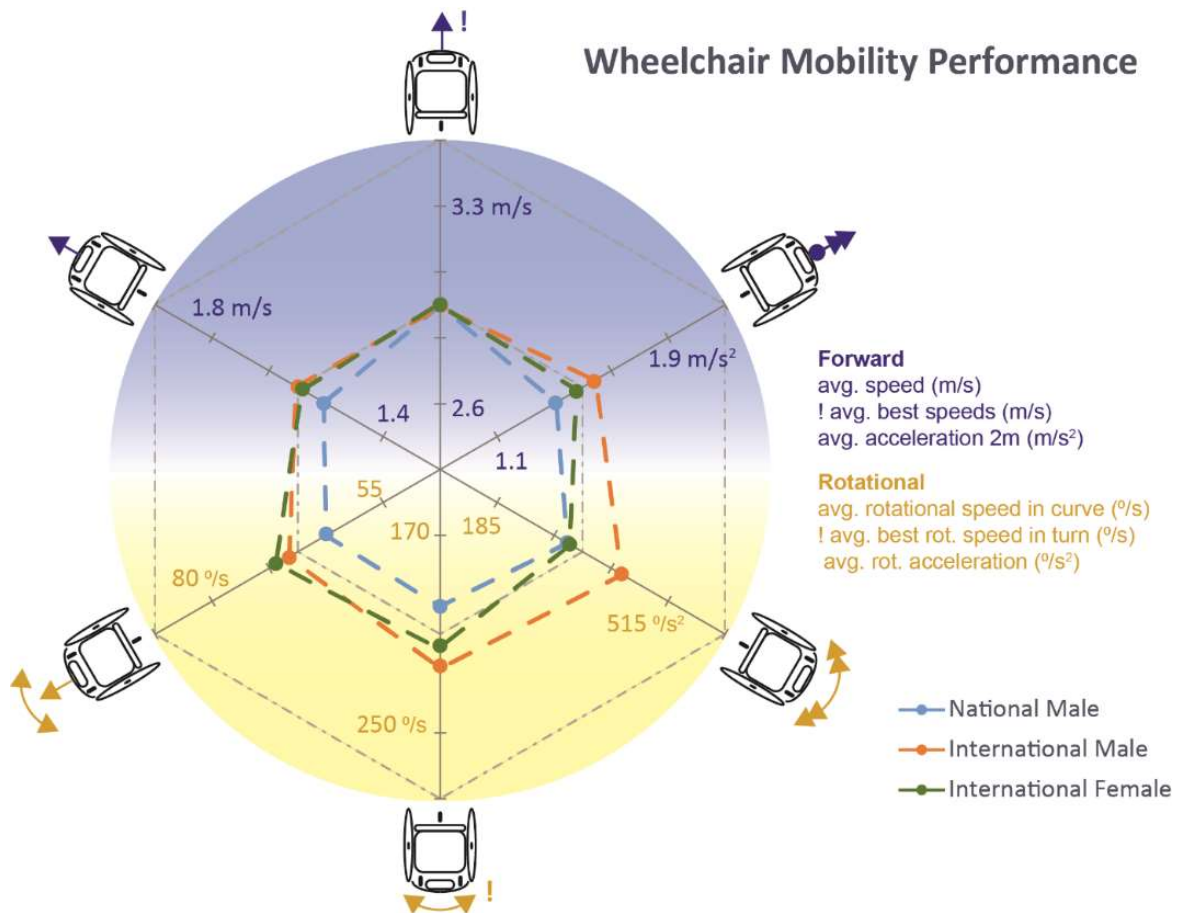


Figure 4.4: Wheelchair mobility performance plot for three competition level groups. National level athletes perform below average on all aspects, although best forward speed (top) is similar for all groups. International male athletes perform best on all kinematic outcomes, except average rotational speed in a curve, in which international females perform best. In all kinematic outcomes except average rotational acceleration, female internationals perform close to their male counterparts.

#### *Performance and selected kinematic outcomes*

Once reduced to the six key outcomes, this set of kinematic outcomes was tested for differences in wheelchair mobility performance between impairment classification levels. For each kinematic outcome a univariate ANOVA was performed with classification as independent factor. Table 4.3 shows that classification is a significant factor ( $p < 0.05$ ) in each GLM after the Holm-Bonferroni correction ( $p < 0.008 - 0.05$ ). To test if the effects for classification hold for all competition levels, two-way ANOVA's with the interaction of classification and competition level as independent factor was performed. The effect of classification on average rotational speed in a curve appeared to be significantly different over competition level groups. The interaction did not show to be significant in the ANOVA's of the other five outcomes after Holm-Bonferroni correction, although two of them were borderline significant (Table 4.3).

Table 4.3: The p value of classification and the interaction of classification with competition level in univariate GLMs for each of the selected kinematic outcomes (see Table 4.2 for abbreviations). \* indicates significant p values ( $p < 0.05$ ) after Bonferroni-Holms correction (see p limit right columns).

Direction	Order	Type	Avg or Best	Component	One way ANOVA classification		Two way ANOVA classification*level	
					p	p limit	p	p limit
Ro	Sp	Turn2	Best	1	.006*	.017	.170	.025
Ro	Acc		Avg	2	.038*	.050	.109	.017
Fo	Acc	2m	Avg	3	.004*	.013	.058	.013
Fo	Sp		Avg	4	.002*	.010	.023	.010
Ro	Sp	Curve2	Avg	5	.001*	.008	.000*	.008
Fo	Sp		Best	6	.014*	.025	.416	.050

## Discussion

A new standardised measure of wheelchair mobility performance is presented, based on a concise yet meaningful set of wheelchair kinematic outcomes that discriminate well between wheelchair basketball athletes of different performance levels.

To avoid overly substantial data reduction at this stage, a selection in the principal component analysis was made based on the second point of inflexion in the scree plot (Figure 4.2). Future analysis on enlarged datasets might point at possibilities for more profound data reduction, without significant information loss. For each of the six PCA components one kinematic outcome was selected. This selected outcome was not per se the one with the highest loading, but *one* of the *three* outcomes with the highest loadings. This selection criterion made it feasible to select a set of kinematic outcomes that was nicely distributed, in terms of direction of movement and average or best performance, while still representing all different PCA components found.

The athlete's classification, assumed to be related to mobility performance level, showed to be a significant factor in univariate GLMs of all selected kinematic outcomes. For one of the key kinematic outcomes (average rotational speed in a curve) a significant interaction between classification and competition level appeared. This may imply that classification is not a similar factor in all competition level groups for this outcome. Graphical display of the results (Figure 4.5) show that the outcomes of the female internationals deviate from the national and international males, particularly in the athletes classified as 2.5. If analysed separately (male/female), classification still appeared to be a significant factor in GLM models, but then results were drawn from very small data set per group. Future enlarged datasets should point out if indeed classification has a different effect on average rotational speed in a curve for female internationals, compared to males.

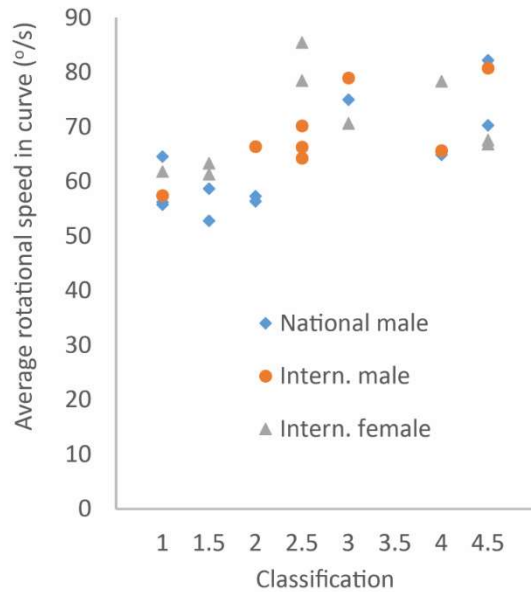


Figure 4.5: Distribution of average rotational speed in a curve (forward speed > 1.5m/s) per classification, grouped by competition level. The deviating scores (particularly for class 2.5) of the international females clarifies the interactional effect found between classification and competition level, since it disturbs the variance per classification used in the GLM.

GLMs showed classification as a significant factor in wheelchair performance, but without designating which athletes (classification groups) perform best. Figure 4.3 shows the wheelchair mobility performance for three classification groups, somewhat equally distributed by competition level. Not surprisingly and in accordance with findings in wheelchair rugby (Sarro et al., 2010; Sporer et al., 2009), higher classified athletes achieve higher best and average speeds during match play. Rotational speeds were higher for higher classified athletes, both in a turn (below average forward speed) and in a curve (above average speed). Higher classified athletes also showed higher average acceleration from standstill and higher average rotational acceleration. Similar conclusions were drawn by Rhodes who reported more high intensity activity in higher classified wheelchair rugby players (Rhodes et al., 2015). Next to these more general tendencies of higher classified athletes being faster and performing at higher intensity (higher average acceleration), the current graph nicely shows that 2 -3 classified athletes perform in-between low (1 – 1.5) and high (4 -4.5) classified athletes concerning forward movement, but perform close to the high classified athletes in rotational movement. Additional measurements should point out if this is a general performance pattern or that it is partially affected by the slightly higher number of male internationals in this particular group.

Differences between competition level groups amply stay within the variance in wheelchair mobility of athletes with different classifications (Figure 4.4). Again, the new graph not only allows to rate the performance level in general, but also shows that international level female athletes perform similar to their male counterparts concerning (rotational) speeds, but at a



reduced intensity. So, the wheelchair mobility graph allows for straightforward, yet detailed comparison of athlete groups.

Next to group wise analysis, the wheelchair mobility performance graph also supports individual athlete comparisons, as can be seen in the example of Figure 4.6 showing the results of three similarly classified male international players. To support evaluation of individual training schedules or wheelchair interventions, the wheelchair mobility performance measurements could be performed on a regular basis, to display results of consecutive measurements.

The current measurements show wheelchair mobility performance *in a match*, not necessarily (isolated) best performance. Additionally, athletes could be tested for maximal performance outside the match to exclude effects of field position (guard, forward and centre), opponents and other match specific conditions that affected wheelchair mobility performance. In that way match mobility performance could be compared to maximal (unconstrained) performance. It can be expected that lowly classified athletes with more severely affected aerobic capacity show more difference between average match performance and isolated best performance, than highly classified athletes. Those research outcomes might provide further insight in the athlete-wheelchair interaction and the possible ways to optimize the wheelchair, train the athlete or optimize match tactics.

As in all wheelchair sport related research, the heterogeneity of athletes made it hard to select a representative sample for each classification group. Expanding the number of athletes measured might slightly shift group averages and significance of differences between groups found. For the international level measurements, only friendly match play was included, which could also have had an effect on the performances shown by the athletes. However, all of the friendly matches were part of a preparation for international tournaments, with opponents of a high competitive level.

The new method to display wheelchair mobility performance is easy to interpret and yet discriminative. Using this generally applicable and yet detailed quantification of mobility performance allows for effective evaluation of interventions regarding wheelchair design, changes in wheelchair settings or changes in athlete training. In that way, it is an important tool to evaluate the effect of any future innovation aiming at improving wheelchair mobility performance, not only in wheelchair basketball, but also in any wheelchair-based sport. Future research should be directed at finding sport specific mobility performance profiles, based on the key kinematics of wheelchair mobility performance.

We believe to have laid out a practical and reliable tool for measuring wheelchair mobility performance that is valuable for performance evaluation and usable for researchers, coaches and athletes.

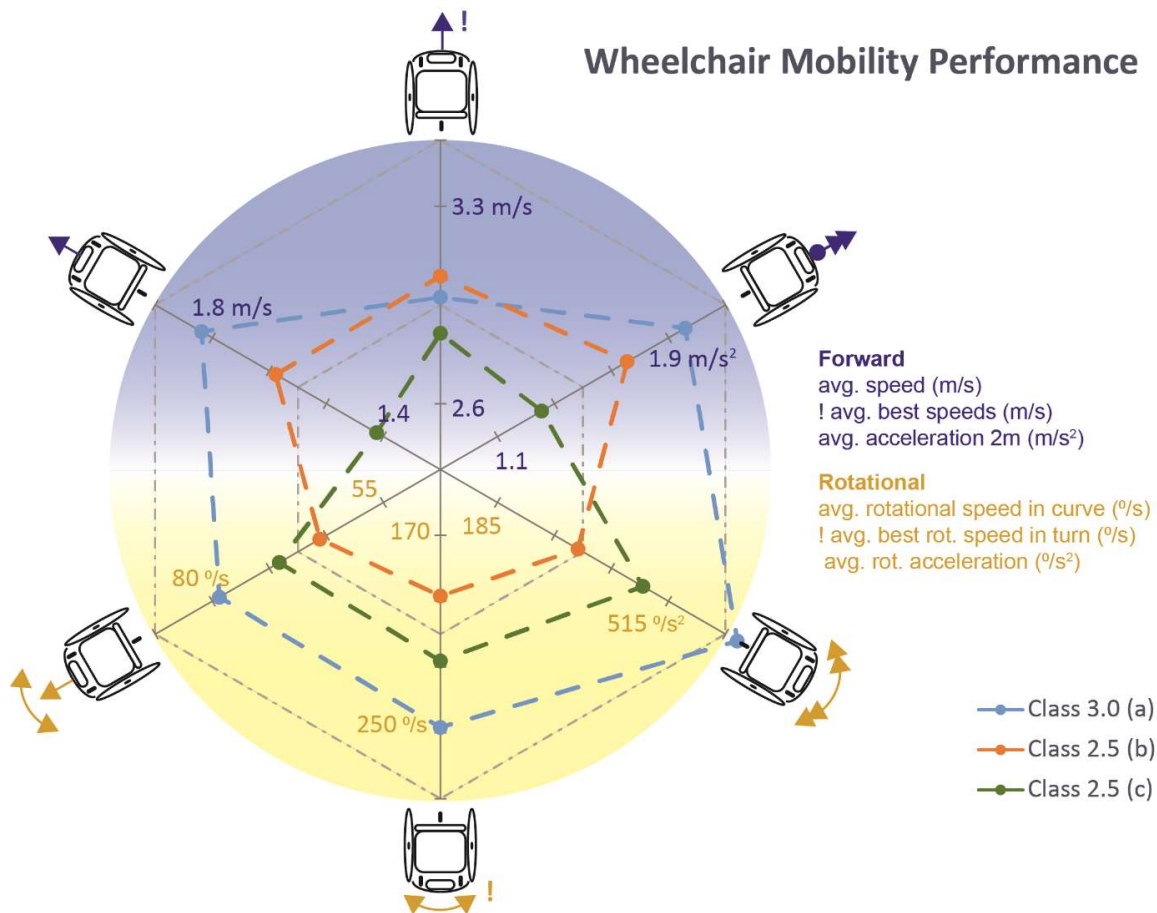


Figure 4.6: Typical example of the wheelchair mobility performance plot for three individual similar classified international male athletes. The class 3 athlete (a) was very skilled and has a high above knee amputation, so a positive power to weight ratio and low moment of inertia, resulting in high (rotational) speeds and accelerations. The two class 2.5 athletes have different wheelchair settings, with b below average and c above average seat height, adjusted to their field role (guard and centre respectively).

Conflict of interest statement

None.

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## Appendix A

Table 4.4: Overview of athlete and wheelchair characteristics

Classification	Field Position	Sex	Level	Wheel diameter (cm)	Rim diameter (cm)	Camber Angle (deg.)	Caster diameter (cm)	Seat depth (cm)	Seat height rear (cm)	Seat height front (cm)	Backrest height (cm)	Seat to footrest (cm)	Backrest to centre axle (cm)	Centre axle to caster (cm)	Centre axle to footplate (cm)	Between wheels (cm)	Between rims (cm)	Track width (cm)	Pivot centres (cm)
1.5	Forward	m	National	61	55	19	7	40	49	52	20	38	14	38	42	38	50	78	38
3.0	Forward	m	National	61	56	19	8	37	53	53	20	42	15	38	41	38	48	78	32
4.5	Center	m	National	65	58	18	7	40	56	56	13	54	17	42	46	42	52	83	37
1.5	Guard	m	National	62	55	16	7	37	51	57	23	49	13	47	37	43	52	76	43
1.0	Forward	m	National	65	59	16	6	42	49	60	30	50	13	52	50	44	52	80	27
4.5	Center	m	National	65	59	13	6	37	54	57	16	51	13	60	60	46	55	75	36
1.0	Guard	m	National	65	59	17	6	40	47	57	28	47	15	48	48	46	56	84	28
4.0	Center	m	National	68	59	13	6	43			20		15			39		70	50
2.0	Guard	m	National	65	59	16	6	36	51	55	22	45	16	47	47	44	54	80	31
4.0	Center	m	National	69	62	18	8	44	59	57	18	51	16	40	48	42	51	84	38
1.0	Forward	m	National	64	59	16	6	37	51	55	30	51	11	50	45	42	50	78	30
2.0	Forward	m	National	64	57	17	7	30	54	64	55	41	13	41	34	33	43	71	32
4.0	Center	m	Intern.	68	62	18	7	46	58	55	19	49	23	38	38	39	46	81	39
1.0	Guard	m	Intern.	62	52	19	7	38	44	54	30	47	15	38	38	44	53	84	35
2.5	Guard	m	Intern.	64	58	19	7	31	56	53	20	38	18	39	39	45	53	86	32
2.5	Center	m	Intern.	67	62	18	7	42	61	61	24	52	16	45	45	42	53	83	41
3.0	Guard	m	Intern.	62	56	18	6	40	47	47	15	0	13	37	0	37	47	75	30
2.5	Guard	m	Intern.	59	53	19	7	40	38	47	20	40	18	40	42	44	51	81	35
4.5	Forward	m	Intern.	65	58	18	8	40	54	57	18	52	18	42	42	41	49	80	23
2.0	Guard	m	Intern.	60	55	19	8	30	36	49	23	45	16	45	43	40	48	80	36
1.0	Forward	f	Intern.	62	57	18	6	33	60	60	17	45	14	42	42	40	48	79	27
3.0	Forward	f	Intern.	64	58	18	8	40	54	56	17	42	17	40	36	40	50	80	33
4.5	Center	f	Intern.	64	58	19	8	36	60	58	16	47	17	44	28	40	50	81	32
2.5	Forward	f	Intern.	65	60	19	6	42	49	58	28	36	14	40	37	40	48	82	30
1.5	Guard	f	Intern.	65	60	17	6	45	50	58	30	46	16	44	43	38	46	75	29
4.5	Guard	f	Intern.	62	56	18	8	38	46	50	12	42	16	43	33	39	49	77	32
2.5	Guard	f	Intern.	60	54	18	6	32	45	54	21	38	14	37	38	40	48	76	29
1.5	Guard	f	Intern.	60	54	18	55	38	45	54	26	45	15	41	32	39	47	76	28
4.0	Forward	f	Intern.	64	59	19	6	36	59	58	15	49	16	43	35	40	49	81	26

## Appendix B

### *Outcomes of wheelchair kinematics*

The IMU based measurement method for measuring wheelchair kinematics as described by van der Slikke et al. (2015a) provides information on movement and direction of movement of the wheelchair. This information is the basis for a wide variety of kinematic outcomes available to outline wheelchair movement during the measurement. This appendix describes the outcomes (Table 4.5) and their structure used.

#### **Forward and rotational movement**

Forward movement is defined as movement perpendicular to the wheels. If the wheelchair is moving in a curve, the line that describes the path of the midpoint of the camber bar is regarded as forward movement. Next, forward movement can be described by displacement, speed and acceleration. The (rotational) acceleration outcomes require a special approach, since for each movement from stand still to stand still, the average (rotational) acceleration is zero. Therefore, for each section of 2 m from standstill the average forward acceleration was calculated and similarly for each rotation of 60° from stand still or straight forward movement, the average rotational acceleration was calculated.

Rotational movement describes the changes in orientation of the wheelchair in the horizontal plane, so the (change in) movement direction. In a “turn on the spot” there is only rotation of the wheelchair, without (significant) forward displacement. Whereas a “curve” is defined as the combination of forward movement with rotation. Like forward movement rotation could be described by rotation angle, rotational speed and rotational acceleration. For rotational speed absolute values were taken, so left and right direction rotations were merged, since previous analysis did not show significant differences between rotational directions.

#### **Thresholds**

To classify rotational movements into either turn or curve, thresholds had to be selected. In the selection that was used prior to principal component analysis (PCA) both categories were calculated with two different thresholds. For the purest turn, only backward or forward speed of maximal 0.5 m/s was allowed (-0.5 – 0.5 m/s). In a less, stringent defined turn (“turn 2”), all speeds below average were included (<1.5 m/s). For the curve one outcome describes the occurrences of rotation around average forward speed (1.5 m/s, with thresholds of 1 – 2 m/s). The second curve outcome (“curve 2”) describes rotations at above average speed (1.5 m/s).

#### **Average or best**

To summarize the complete measurement averages of outcomes were calculated such as average speed. Like described in the method section, the measurement was also split in discrete sections of movement (of at least 0.5s) that also provided kinematic outcomes per section. These outcomes were either averaged (general match performance) or the best 5 outcomes were averaged (best match performance). For the selected outcomes in PCA, the

forward movements of at least 2m occurred on average 165 (+/- 53) times and the rotational movements 560 (+/- 161) per measurement. So, the best forward speed is 5 out of 165 (on average) and the best turn comprises 5 out of 560 (on average).

**Table 4.5: Overview of all kinematic outcomes used for principal component analysis.**

Outcome number	Description
1	Average forward speed (m/s)
2	Average of best 5 forward speeds (m/s)
3	Average absolute forward acceleration (m/s <sup>2</sup> )
4	Average of all average accelerations (m/s <sup>2</sup> ) to 2 m from stand still
5	Average of best 5 average accelerations (m/s <sup>2</sup> ) to 2 m from standstill
6	Average absolute rotational speed (°/s)
7	Average absolute rotational speed (°/s) in a turn, fs between -0.5 and 0.5 m/s
8	Average absolute rotational speed (°/s) in a turn2, fs below 1.5 m/s
9	Average absolute rotational speed (°/s) in a curve, fs between 1 and 2 m/s
10	Average absolute rotational speed (°/s) in a curve2, fs above 1.5 m/s
11	Average of best 5 absolute rotational speeds (°/s)
12	Average of best 5 absolute rotational speeds (°/s) in a turn, fs between -0.5 and 0.5 m/s
13	Average of best 5 absolute rotational speeds (°/s) in a turn2, fs below 1.5 m/s
14	Average of best 5 absolute rotational speeds (°/s) in a curve, fs between 1 and 2 m/s
15	Average of best 5 absolute rotational speeds (°/s) in a curve2, fs above 1.5 m/s
16	Average absolute rotational acceleration (°/s <sup>2</sup> )
17	Average absolute rotational acceleration (°/s <sup>2</sup> ) in a turn, fs between -0.5 and 0.5 m/s
18	Average absolute rotational acceleration (°/s <sup>2</sup> ) in a turn2, fs below 1.5 m/s
19	Average absolute rotational acceleration (°/s <sup>2</sup> ) in a curve, fs between 1 and 2 m/s
20	Average absolute rotational acceleration (°/s <sup>2</sup> ) in a curve2, fs above 1.5 m/s
21	Average of all average rotational accelerations (°/s <sup>2</sup> ) to 60° from stand still
22	Average of best 5 average rotational accelerations (°/s <sup>2</sup> ) to 60° from standstill

## Appendix C

### *Outcome selection*

Given the aim of this research to provide a useful tool for both scientists and athletes, the selection of outcomes was not done based on strict PCA conditions alone, but the chosen method allowed for minimal leeway. This appendix describes the interpretation of the selection concept as described in the method section. Concept wise the most elegant selection would be a “best” and “average” outcome of (rotational) speed and (rotational) acceleration, resulting in eight outcomes. Based on the criteria used, only six components were selected. To retain an even distribution between forward and rotational movement, the “best” or “average” outcome of one magnitude needed to be dropped.

Table 4.2 shows all retained (n=6) components and the loading of each kinematic outcome. The first component has by far the highest explained variance, so for this selection no compromise was made and the outcome with the highest loading was selected (best rotational speed in turn2). The loading (second best) on component 2 and 3 allowed for the selection of average (rotational) acceleration, which is a very straight forward and stable outcome,

representing the intensity of wheelchair performance. For component 6, only one outcome loaded substantially (best forward speed), so this one was selected. For component 5, only rotational speeds loaded, so the outcome with the highest loading was selected (average rotational speed in curve2). To keep an even distribution between forward and rotational movement, for component 4 the third best outcome was selected (average forward speed). So, in conclusion, in three cases the outcome with the highest loading per component was selected, in one case (component 2) the second-best outcome was chosen but with minimal difference to the best and finally for two components (2 & 4) conceptual motivations prevailed somewhat over outcome loading on the component.

A close-up, low-angle photograph of a wheelchair's metal frame. The frame is made of polished, reflective metal tubes. A white, rectangular sensor device with a small orange circular light on top is mounted to the frame. The background is a bright, out-of-focus white light, creating a strong contrast with the dark metal.

# Chapter 5

## A field-based wheelchair mobility performance test

Development, construct validity and test–retest reliability of a field-based wheelchair mobility performance test for wheelchair basketball.

*Journal of Sports Sciences*





## Chapter 5: A field-based wheelchair mobility performance test

### Development, construct validity and test–retest reliability of a field-based wheelchair mobility performance test for wheelchair basketball.

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#### Abstract

The aim of this study was to develop and describe a wheelchair mobility performance test in wheelchair basketball and to assess its construct validity and reliability. To mimic mobility performance of wheelchair basketball matches in a standardized manner, a test was designed based on observation of wheelchair basketball matches and expert judgement. Forty-six players performed the test to determine its validity and 23 players performed the test twice for reliability. Independent-samples t-tests were used to assess whether the times needed to complete the test were different for classifications, playing standards and sex. Intraclass Correlation Coefficients (ICCs) were calculated to quantify reliability of performance times.

Males performed better than females ( $p < 0.001$ , effect size  $ES = -1.26$ ) and international men performed better than national men ( $p < 0.001$ ,  $ES = -1.62$ ). Performance time of low ( $\leq 2.5$ ) and high ( $\geq 3.0$ ) classification players was borderline not significant with a moderate  $ES$  ( $p = 0.06$ ,  $ES = 0.58$ ). The reliability was excellent for overall performance time ( $ICC = 0.95$ ). These results show that the test can be used as a standardized mobility performance test to validly and reliably assess the capacity in mobility performance of elite wheelchair basketball athletes. Furthermore, the described methodology of development is recommended for use in other sports to develop sport-specific tests.

## Introduction

In wheelchair court sports, the player, the wheelchair and the environment determine performance. All the activities an athlete does (or can do) with a wheelchair, the wheelchair-athlete activities, can be defined as mobility performance. Key determinants of mobility performance are the abilities of the athlete to accelerate, sprint, brake and turn with the wheelchair (de Witte et al., 2016; Mason, Porcellato, van der Woude, & Goosey-Tolfrey, 2010). The actual mobility performance in wheelchair court sports should be assessed during a match, preferably by systematic (video) observation combined with the use of (inertial) sensors (Bloxham et al., 2001; de Witte et al., 2016; Rhodes et al., 2014). These observations and measurements during wheelchair basketball result in, for example, findings that players move across the field with light or no arm strokes for 24% (standard deviation [SD] 7) of the time (Bloxham et al., 2001) and that national standard players drive relatively more forward, while international standard players perform more rotational movements during a match (de Witte et al., 2016). Assessing mobility performance is a fundamental requirement for trainers and coaches to, for example, develop training schemes, discuss and improve the athlete's level of performance, detect strength and weaknesses of mobility performance and develop optimal wheelchair configurations. The use of systematic observation and/or sensor technology during matches can thus provide useful information about mobility performance. However, systematic observation is very time-consuming and results of both methods are influenced by the continuously changing environment when participating in a match of wheelchair basketball. Each match has unique circumstances depending on, for example, the opponent, injuries or team composition.

In order to repeatedly monitor athletes' mobility performance, athlete performance on a standardized field-based test is assigned to be informative and helpful (Goosey-Tolfrey & Leicht, 2013; Vanlandewijck, Spaepen, & Lysens, 1995). Currently, there is no generally accepted validated mobility performance test available for wheelchair court sports in general and for wheelchair basketball specifically. To assess and monitor mobility performance in a controllable setting, the mobility performance during a match must be simulated. A simulation or test that is based on field activities – i.e. the match – will result in meaningful information for coaches, players and (embedded) scientists. Field-based tests are generally acknowledged as a feasible way to get an indication of the performance standard of athletes (de Groot, Balvers, Kouwenhoven, & Janssen, 2012). Field-based tests exist for wheelchair court sports, but they assess mainly other aspects of performance, such as game performance (ball skills) and athlete performance (e.g. maximal heart rate or oxygen consumption) and only some parts of mobility performance (Barfield & Malone, 2012; Byrnes & Hedrick, 1994; de Groot et al., 2012; de Groot, Valent, Fickert, Pluim, & Houdijk, 2016; Gil et al., 2015; Granados et al., 2015; Yilla & Sherrill, 1998).

Extensive systematic observation and analyses of mobility performance during wheelchair basketball matches have recently been done for wheelchair basketball (de Witte et al., 2016; van der Slikke, Berger, Bregman, & Veeger, 2016). These data were used to develop a standardized and worldwide-accepted wheelchair mobility performance (WMP) test. Feasibility is a precondition in the development process and the test should be easy to take without advanced equipment. To further ensure a high external validity, the test should be performed by wheelchair basketball players in their own sports wheelchair and on a regular wheelchair basketball court. Furthermore, the test should discriminate between different categories of athletes (e.g. sex and playing standard), which is known from the literature that they differ in mobility performance (de Witte et al., 2016; Gómez, Pérez, Molik, Szyman, & Sampaio, 2014; van der Slikke, Berger, Bregman, & Veeger, 2015b; van der Slikke et al., 2016; Vanlandewijck, Daly, Spaepen, Theisen, & Pétré, 1999). Besides valid results, the test should give reliable data to monitor the actual capacity in mobility performance of athletes.

In this context, the goals of the present study were (1) to describe the development of a field-based wheelchair test that assesses mobility performance capacity and which closely mimics the wheelchair mobility skills required in real wheelchair basketball matches, (2) to define the developed field-based test and (3) to assess the construct validity and test-retest reliability of the newly developed field-based WMP test for wheelchair basketball.

## Methods

### *Test development*

The development process had a stepwise character: (1) examine match mobility performance, (2) determine practical test requirements and (3) organize expert meetings to verify the test design.

To examine mobility performance in matches, coaches were interviewed to describe and define wheelchair-athlete activities during wheelchair basketball. The wheelchair activities were assessed by systematic observation of video footage of matches (de Witte et al., 2016). Four matches at national playing standard and five matches at international playing standard were recorded. In total, 56 male wheelchair basketball players were analysed during an entire match. Time-motion analysis was used for determining the frequency and duration of these athlete and wheelchair activities (de Witte et al., 2016). Based on the results, wheelchair basketball mobility performance was defined in various dominant game-related wheelchair activities (Table 5.1). In order to make a translation from match data to test design, the output was organized into three main categories: separate activities, combined activities and activities with ball possession. For each of these categories the most common wheelchair-athlete activities and distances were determined with inertial sensors (van der Slikke et al., 2016).

In addition, practical test requirements were formulated for the WMP test based on interviews with coaches and experts: (1) The WMP test should be easy to use without advanced

equipment; (2) The WMP test should take place in a realistic environment common to wheelchair basketball, e.g. athletes performed the test in their own sports wheelchairs and on a regular wheelchair basketball court and (3) Fatigue should not be a limiting factor for performance. The observed activities and the requirements were used to draft the first test setup.

An expert meeting with coaches, players and researchers was organized to discuss the first version of the WMP test to increase its content validity, after which “specific skills” were added as a fourth main group. The four main groups contained a total of 15 different wheelchair-athlete activities (Table 5.2). Based on these data a final version of the WMP test was developed which is described in the results section. The development process took place between March 2014 and March 2015.

**Table 5.1: Overview of the relative duration ( $\pm$ SD) as a percentage of wheelchair-athlete activities based on video analysis of 56 male wheelchair basketball athletes playing at national and international playing standard (de Witte et al., 2016). The data are complemented with information from data of inertial sensors based on 29 wheelchair basketball players (van der Slikke et al., 2016).**

Main group	Activity	Distance	Direction
Separate activities	Driving forward	12 m	--
	Rotation	Radius 1.9 m (total circumference of 12 m)	Clockwise/ Counterclockwise
	Rotation on the spot		Clockwise/ Counterclockwise
Combined activities	Driving forward with two stops	3, 3 and 6m = 12 m	--
	Rotation with two stops	90° (3m), 90° (3m), 180° (6m) = 12 m	Clockwise/ Counterclockwise
	Rotation on the spot with stop	90°, 90°	Clockwise/ Counterclockwise
	Combined activities		--
Specific skills	Tik-Tak Box		--
Activities with ball possession	Driving forward	12 m	--
	Rotation	Radius 1.9m (total circumference of 12 m)	Clockwise/ Counterclockwise

**Table 5.2: Setup test protocol based on observed wheelchair-athlete activities and distances.**

Wheelchair activities	Outcome video analysis Relative duration ( $\pm$ SD)	Relative duration during ball possession % ( $\pm$ SD)	Outcome inertial sensors
Standing still	19 (6)	26 (16)	--
Driving forward	45 (6)	42 (12)	Most common: 3 m Maximal: 12 m
Driving backward	2 (1)	1 (1)	--
Rotate	29 (8)	28 (12)	Most common: radius 1.5-2.5 m
Brake	3 (2)	2 (2)	--

### *Construct validity and test-retest reliability*

To evaluate the construct validity and reliability of the newly developed WMP test, experienced wheelchair basketball players were included in different field-based standardized experimental sessions.

### **Participants**

For the validity study, 46 players - competing at different playing standards - were included, and for the reliability study, 23 players - competing at a national playing standard (Dutch first division competition) - participated. In the validity group, a distinction was made between men and women competing at an international standard and players competing at a national standard, and a distinction was made between low classification ( $\leq 2.5$  points) and high classification ( $\geq 3.0$  points) players. The International Wheelchair Basketball Federation uses a classification system based on the players' functional potential to execute fundamental basketball movements (Xu et al., 2010). All players are scaled from 1 (minimal functional potential) to 4.5 points (maximal functional potential) on an ordinal functional level scale. The characteristics (classification, basketball experience and age) of the validity and reliability study groups are shown in Table 5.3. Players were informed about the procedures before given their written informed consent. This study was approved by the Ethical Committee of the Department of Human Movement Sciences, Vrije Universiteit Amsterdam, the Netherlands.

**Table 5.3: General characteristics of the participants included in the construct validity (n=46) and test-retest reliability (n=23) analyses for classification 1-4.5.**

	Classification	n	Experience in years (±SD)	Age in years (±SD)	Mean (±SD) and range of wheel size (cm)	Mean (±SD) and range of elbow angle with hand on the top of the rim (°)	Mean (±SD) and range of wheel camber (°)	Men playing at International standard (n)	Women playing at International standard (n)	Men playing at National standard (n)
Validity study	1-1.5	8	7.2 (4.8)	28.3 (7.1)	62.0 (2.4) 58 - 64	100 (11) 86 - 122	17 (1) 16 - 19	3	3	2
	2-2.5	11	12.9 (6.9)	28.9 (9.3)	62.8 (2.6) 59 - 68	117 (18) 77 - 135	17 (1) 15 - 19	6	3	2
	3-3.5	8	9.1 (3.3)	26.7 (10.0)	64.4 (1.1) 64 - 67	128 (18) 100 - 162	18 (1) 17 - 21	5	3	-
	4-4.5	19	8.4 (5.2)	24.7 (8.3)	64.5 (2.0) 61 - 68	136 (18) 99 - 168	18 (1) 15 - 21	7	4	8
Reliability study	1-1.5	2	4.0 (0.7)	21.0 (4.2)	61.5 (3.5) 59 - 64	87 (1) 86 - 88	17 (1) 16 - 17	-	-	2
	2-2.5	1	9.0	21.0	61.0	110	17	-	-	1
	3-3.5	5	6.4 (1.9)	16.8 (5.1)	60.4 (2.9) 58 - 64	104 (24) 81 - 136	18 (2) 15 - 20	-	-	5
	4-4.5	15	6.5 (6.4)	22.8 (10.8)	63.4 (2.5) 56 - 67	129 (16) 99 - 151	18 (1) 15 - 20	-	-	15

## Procedure

Prior to all tests, procedures were explained and the test protocol was demonstrated using a video shown to all participants. Players were asked to refrain from smoking and drinking caffeine or alcohol at least 2 h prior to the WMP test. Before performing the WMP test, players carried out a self-selected warm up. All players performed the WMP test in their own sports wheelchairs, with their own configurations and tires were inflated to 7 bars.

Participants of the validity study performed the WMP test once on the same synthetic soft-top basketball court. Participants were measured while being involved in training sessions and in the Euro Cup 4 tournament (April 2015, the Netherlands).

Participants of the test-retest reliability study performed the same test twice. Participants were tested during their training sessions, on the basketball courts where the teams trained, on two separate days at the same time of the day, with 1 week in between (October/November 2015).

## Data acquisition and analyses

The WMP test simulated the 15 most common wheelchair-athlete activities during wheelchair basketball (Table 5.2). All the standardized activities were carried out in succession, separated by standardized rest periods to avoid fatigue. Two high-definition video cameras (CASIO EX-FH100, 1280\*720, 20-240mm) were placed at the side of the test. Each camera was focused on one half of the basketball court with a small overlap between the videos. The outcome of the WMP test was time (s), which was manually recorded from video analysis (Kinovea 0.8.15, available for download at: <http://www.kinovea.org>). These analyses resulted in 16 performance time values, one for each of the 15 wheelchair-athlete activities (*time activity no. 1 - 15*) and the *overall performance time*, which is the sum of the performance times of the 15 separate activities.

## Statistical analyses

All statistical analyses were performed using IBM SPSS statistics version 22 (IBM Corporation, Armonk, NY, USA). Descriptive statistics for the *time activities no. 1-15* and the *overall performance time* were presented as mean  $\pm$  SD. The assumptions of normality were checked with the Shapiro-Wilk test, as well as z-values of the skewness and kurtosis. Also, histograms, boxplots and q-q plots of the data were visually inspected. The assumption of normality was not violated.

## Construct validity

To determine the construct validity of the WMP test, three hypotheses were formulated and tested. Hypothesis (1): Players with a high classification ( $\geq 3.0$  points) are expected to perform better than players with a low classification ( $\leq 2.5$  points) (van der Slikke et al., 2015b; Vanlandewijck et al., 1999). Hypothesis (2): Players playing at an international standard are expected to perform better than players at a national standard (de Witte et al., 2016; van der Slikke et al., 2015b). Hypothesis (3): Men are expected to perform better than women because

of sex differences in upper body strength and trunk stability as key determinants of mobility performance (Cohen, 1988).

To assess potential differences in the 16 performance time outcomes between classification categories, playing standards and sex, independent samples t-tests were used. The means  $\pm$  standard deviations were completed with mean differences, 95% confidence intervals of the difference and p-values. Differences with p-values  $<0.05$  were considered statistically significant. In addition, Cohen's d effect sizes (ES) were calculated for main effects as outlined by Cohen (Cohen, 1992). The (absolute) magnitude of the ES was classified as large ( $\geq 0.80$ ), moderate (0.50-0.79) or small ( $<0.50$ ) (Cohen, 1988).

### ***Test-retest reliability***

Test-retest reliability of the 16 time performance outcomes was evaluated with Intraclass Correlation Coefficients (ICC(3,1)), Standard Error of Measurement (SEM) and Limits of Agreement (LoA). ICC(3,1) is a two-way mixed single measure of absolute agreement (Shrout & Fleiss, 1979). ICC scores  $\geq 0.70$  are indicated as satisfactory, values  $\geq 0.75$  are considered as good and values  $\geq 0.90$  are categorized as excellent reliability (Atkinson & Nevill, 1998). The SEM for agreement was calculated with Equation (1).

$$SEM_{agreement} = \sqrt{Var_o + Var_{residual}} \quad (1)$$

Variance components were obtained from variance component analyses and two components were estimated, variance attributable to observers ( $Var_o$ ) and residual error ( $Var_{residual}$ ).

The Bland-Altman method was used to examine the differences between the WMP test and retest for the whole group, including the calculation of the mean difference between the test and retest, the SD of the difference and the 95% LoA (Bland & Altman, 1986). The LoA95 was calculated with Equation (2).

$$LOA95 = mean\ difference \pm 1.96 * SD\ difference \quad (2)$$

The differences for the overall performance times were visualized in a Bland-Altman plot, where the individual differences between the test and retest are plotted against the mean of the test and retest.

## **Results**

### ***Design of the WMP test***

The final version of the WMP test for wheelchair basketball consisted of 15 activities with a standardized period of rest between the activities. The WMP test is divided into four main groups. Group (1): Separate activities containing a 12-m sprint, a rotation with a curve



(circumference) of 12-m (clockwise/counter clockwise) and a turn on the spot (clockwise/counter clockwise); Group (2): Combined activities containing the same activities as group 1, combined with starts and stops in between; Group (3): Specific skills consisting of a tik-tak box, which means performance of short movements forward and backward alternated with collisions against a stationary object. Group (4) a 12-m sprint and rotation (clockwise/counter clockwise) with a curve (circumference) of 12-m performed with ball possession (dribble) (for the total WMP test protocol and the sequence of the activities, see Supplementary material).

#### *Construct validity and test-retest reliability*

Time scores of the tik-tak box (activity no. 1) of the WMP test were not included in both the reliability and the construct validity study. The start and stop times of this activity were not clearly visible at the video-analysis, and because of this, the data are not presented and included.

#### **Construct validity**

To determine the construct validity of the WMP test, three hypotheses were formulated and tested.

*Hypothesis 1) Players with a high classification are expected to perform better than players with a low classification.* The overall performance time was borderline non-significant between high and low classifications ( $p=0.06$ ,  $ES=0.58$ ) but the magnitude of the ES can be interpreted as moderate (Table 5.4). For time scores on the individual activities, the classification analyses showed significant differences for driving forward movements and turn on the spots, in which high classification players performed the activities faster than low classification players. Significant differences between high and low classifications were observed for the 12-m sprint (mean difference=0.32s;  $ES=0.92$ ) and for the 3-3-6 m sprint (mean difference=0.55s;  $ES=0.81$ ). However, for nearly all activities related to rotation (7 out of 10) there was no difference between classification categories.

*Hypothesis 2) Players playing at an international standard are expected to perform better than players at a national standard.* The WMP test showed a significant difference for playing standard for the overall performance time ( $p<0.001$ ,  $ES=-1.62$ ). International men performed the WMP test on average 8.11s faster than the national men (Table 5.5). The WMP test showed a significant difference between international men and national men for 13 of the 15 outcomes and showed that international men were faster on all the activities (moderate/large ES: 0.81-1.72). The WMP test showed no differences for three of the four activities that measured turn on the spot (no. 2,6 and 10) (moderate/small ES: 0.71 – 0.22).

*Hypothesis 3) Men are expected to perform better than women, both competing at the same playing standard.* There was a significant difference between men and women on the overall performance time ( $p < 0.001$ ,  $ES = -1.26$ ). International men performed the WMP test faster than international women (Table 5.6). In addition, the WMP test showed differences between international men and international women on all activities with the exception of the activities that measured turn on the spot and 12 m dribble. A striking detail is that international women performed the rotation on the spot activities almost as fast as the international men (small  $ES$ : 0.02-0.44).

### **Test-retest reliability**

The test-retest reliability analyses results are summarized in Table 5.7. The ICC value for the overall performance time was excellent ( $ICC = 0.95$ ). The LoA95 show that an improvement of 4.20s (5.1%) can be detected as a real improvement on the WMP test. The Bland-Altman plot for test-retest agreement of the overall performance time is shown in Figure 5.1. The mean difference between the WMP test and retest for the overall performance time was 0.57s ( $\pm 2.14$ ). The variability of the differences between the two measurements seems to be constant over the range of the (mean) performance time scores. The ICC values for the individual activities ranged from 0.25 for the 180° turn on the spot (left) (no. 2) to 0.92 for the combination (no. 15). The four activities that measured turn on the spot (no. 2, 6, 10 and 14) show a low reliability ( $ICC \leq 0.62$ ) while the LoA95 for these activities were high (at least 0.3s, 22.0%).

**Table 5.4: Mean ( $\pm$ SD) performance times (s) for each activity and overall performance time (s) of the wheelchair mobility performance test for classification (classification  $\leq 2.5$  points and classification  $> 2.5$  points) complemented with the mean difference between the classification groups, 95% confidence intervals of the differences and Cohen's d effect sizes.**

		Classifi-	Classifi-	Mean differ-	Standard Error differ-	95% Confidence Interval of the difference		p-values	Effect Size
		cation $\leq 2.5$	cation $> 2.5$			Lower	Upper		
		(n=19)	(n=27)						
		Mean ( $\pm$ SD)	Mean ( $\pm$ SD)						
Activity 2	180° Turn on the spot (left)	0.93 (0.09)	0.84 (0.08)	0.09	0.02	0.04	0.14	0.00*	1.04
Activity 3	12 m sprint	5.12 (0.42)	4.80 (0.28)	0.32	0.10	0.11	0.53	0.00*	0.92
Activity 4	12 m rotation (right)	5.97 (0.41)	5.90 (0.40)	0.07	0.12	-0.17	0.31	0.57	0.17
Activity 5	12 m rotation (left)	5.95 (0.47)	5.89 (0.39)	0.06	0.13	-0.19	0.32	0.62	0.15
Activity 6	180° Turn on the spot (right)	0.95 (0.13)	0.89 (0.12)	0.06	0.04	-0.01	0.14	0.10	0.50
Activity 7	3-3-6m sprint	7.19 (0.77)	6.64 (0.61)	0.55	0.20	0.14	0.96	0.01*	0.81
Activity 8	3-3-6m rotation (left)	7.66 (0.84)	7.33 (0.61)	0.33	0.21	-0.10	0.76	0.13	0.47
Activity 9	3-3-6m rotation (right)	7.58 (0.80)	7.23 (0.61)	0.36	0.21	-0.06	0.78	0.09	0.51
Activity 10	90°- 90° turn on the spot with stop (left)	1.54 (0.19)	1.38 (0.17)	0.16	0.05	0.05	0.27	0.01*	0.87
Activity 11	12 m dribble	6.03 (0.70)	5.80 (0.68)	0.24	0.21	-0.18	0.65	0.26	0.34
Activity 12	12 m rotation dribble (right)	7.38 (0.91)	7.17 (0.87)	0.22	0.26	-0.31	0.75	0.41	0.25
Activity 13	12 m rotation dribble (left)	7.42 (0.97)	7.27 (0.68)	0.15	0.24	-0.34	0.64	0.54	0.19
Activity 14	90°- 90° turn on the spot with stop (right)	1.41 (0.17)	1.31 (0.15)	0.10	0.05	0.00	0.19	0.05*	0.61
Activity 15	Combination	13.95 (0.95)	13.42 (0.67)	0.53	0.24	0.04	1.02	0.03*	0.67
<b>Overall performance time</b> (Sum activities 2 - 15)		79.25 (6.56)	75.95 (4.97)	3.30	1.72	-0.17	6.77	0.06	0.58

\*Significant effect of classification ( $p < 0.05$ ).

**Table 5.5: Mean ( $\pm$ SD) performance times (s) for each activity and overall performance time (s) of the wheelchair mobility performance test for differences in playing standard (international men & national men) complemented with the mean difference between the (international) groups, 95% confidence intervals of the differences and Cohen's d effect sizes.**

		International men (n=21)	National men (n=12)	Mean difference	Standard Error difference	95% Confidence Interval of the difference		<i>p</i> -values	Effect Size
		Mean ( $\pm$ SD)	Mean ( $\pm$ SD)			Lower	Upper		
Activity 2	180° Turn on the spot (left)	0.87 (0.09)	0.89 (0.12)	-0.02	0.04	-0.10	0.05	0.54	-0.22
Activity 3	12 m sprint	4.76 (0.34)	5.08 (0.45)	-0.32	0.14	-0.60	-0.03	0.03*	-0.84
Activity 4	12 m rotation (right)	5.72 (0.42)	6.16 (0.37)	-0.43	0.15	-0.73	-0.14	0.01*	-1.08
Activity 5	12 m rotation (left)	5.67 (0.38)	6.17 (0.38)	-0.51	0.14	-0.79	-0.23	0.00*	-1.33
Activity 6	180° Turn on the spot (right)	0.90 (0.15)	0.95 (0.15)	-0.05	0.05	-0.16	0.06	0.38	-0.32
Activity 7	3-3-6m sprint	6.57 (0.75)	7.17 (0.73)	-0.60	0.27	-1.15	-0.06	0.03*	-0.81
Activity 8	3-3-6m rotation (left)	7.01 (0.71)	7.88 (0.52)	-0.86	0.24	-1.34	-0.38	0.00*	-1.32
Activity 9	3-3-6m rotation (right)	6.91 (0.56)	7.89 (0.60)	-0.99	0.21	-1.41	-0.56	0.00*	-1.72
Activity 10	90°- 90° turn on the spot with stop (left)	1.41 (0.21)	1.55 (0.18)	-0.14	0.07	-0.29	0.01	0.06	-0.71
Activity 11	12 m dribble	5.66 (0.63)	6.25 (0.67)	-0.59	0.23	-1.07	-0.12	0.02*	-0.92
Activity 12	12 m rotation dribble (right)	6.77 (0.69)	7.91 (0.77)	-1.13	0.26	-1.67	-0.60	0.00*	-1.57
Activity 13	12 m rotation dribble (left)	6.88 (0.73)	7.99 (0.72)	-1.10	0.26	-1.64	-0.57	0.00*	-1.52
Activity 14	90°- 90° turn on the spot with stop (right)	1.28 (0.15)	1.49 (0.17)	-0.21	0.06	-0.32	-0.09	0.00*	-1.34
Activity 15	Combination	13.15 (0.70)	14.17 (0.86)	-1.02	0.28	-1.59	-0.45	0.00*	-1.34
<b>Overall performance time</b> (Sum activities 2 - 15)		73.44 (4.95)	81.55 (5.08)	-8.11	1.83	-11.84	-4.37	0.00*	-1.62

\*Significant effect of playing standard ( $p < 0.05$ ).

**Table 5.6: Mean ( $\pm$ SD) performance times (s) for each activity and overall performance time (s) of the wheelchair mobility performance test for differences in sex (international men & international women) complemented with the mean difference between the sex groups, 95% confidence intervals of the differences and Cohen's d effect sizes.**

		International men (n=21)	International women (n=13)	Mean difference	Standard Error difference	95% Confidence Interval of the difference		<i>p</i> -values	Effect Size
		Mean ( $\pm$ SD)	Mean ( $\pm$ SD)			Lower	Upper		
		Activity 2	180° Turn on the spot (left)			0.87 (0.09)	0.89 (0.07)		
Activity 3	12 m sprint	4.76 (0.34)	5.04 (0.27)	-0.28	0.11	-0.50	-0.05	0.02*	-0.90
Activity 4	12 m rotation (right)	5.72 (0.42)	6.07 (0.21)	-0.35	0.12	-0.60	-0.09	0.01*	-0.98
Activity 5	12 m rotation (left)	5.67 (0.38)	6.07 (0.29)	-0.40	0.12	-0.65	-0.15	0.00*	-1.15
Activity 6	180° Turn on the spot (right)	0.90 (0.15)	0.90 (0.07)	0.00	0.04	-0.09	0.09	0.95	0.02
Activity 7	3-3-6m sprint	6.57 (0.75)	7.06 (0.52)	-0.49	0.24	-0.97	-0.01	0.05*	-0.73
Activity 8	3-3-6m rotation (left)	7.01 (0.71)	7.83 (0.45)	-0.81	0.22	-1.27	-0.36	0.00*	-1.30
Activity 9	3-3-6m rotation (right)	6.91 (0.56)	7.65 (0.56)	-0.74	0.20	-1.14	-0.34	0.00*	-1.33
Activity 10	90°- 90° turn on the spot with stop (left)	1.41 (0.21)	1.40 (0.14)	0.01	0.07	-0.14	0.15	0.93	0.03
Activity 11	12 m dribble	5.66 (0.63)	5.95 (0.70)	-0.30	0.23	-0.77	0.17	0.21	-0.45
Activity 12	12 m rotation dribble (right)	6.77 (0.69)	7.44 (0.84)	-0.67	0.26	-1.20	-0.13	0.02*	-0.89
Activity 13	12 m rotation dribble (left)	6.88 (0.73)	7.47 (0.51)	-0.58	0.23	-1.06	-0.11	0.02*	-0.89
Activity 14	90°- 90° turn on the spot with stop (right)	1.28 (0.15)	1.34 (0.10)	-0.06	0.05	-0.15	0.04	0.22	-0.44
Activity 15	Combination	13.15 (0.70)	13.88 (0.55)	-0.73	0.23	-1.20	-0.26	0.00*	-1.12
<b>Overall performance time</b> (Sum activities 2 - 15)		73.44 (4.95)	79.21 (3.88)	-5.76	1.63	-9.08	-2.44	0.00*	-1.26

\*Significant effect of sex ( $p < 0.05$ ).

**Table 5.7: Descriptive values of 23 national male wheelchair basketball players (mean (s)  $\pm$ SD) and mean differences for the test-retest complemented with reliability statistics (s): ICC(3,1) absolute agreement, 95% confidence interval of the ICC agreement, SEM and 95% limits of agreement.**

		Test 1	Test 2	Mean difference ( $\pm$ SD)	ICC agreement	95% confidence interval of the ICC		SEM agreement	Limits of agreement
		Mean ( $\pm$ SD)	Mean ( $\pm$ SD)			Lower	Upper		
Test2	180° Turn on the spot (left)	0.90 (0.15)	0.90 (0.10)	0.00 (0.15)	0.25	-0.19	0.60	0.10	0.30
Test3	12 m sprint	5.02 (0.36)	5.13 (0.42)	-0.10 (0.34)	0.62	0.29	0.82	0.24	0.66
Test4	12 m rotation (right)	6.33 (0.56)	6.33 (0.49)	0.00 (0.23)	0.91	0.80	0.96	0.16	0.45
Test5	12 m rotation (left)	6.33 (0.54)	6.40 (0.56)	-0.08 (0.31)	0.84	0.66	0.93	0.22	0.61
Test6	180° Turn on the spot (right)	0.93 (0.16)	0.90 (0.13)	0.03 (0.14)	0.55	0.20	0.78	0.10	0.26
Test7	3-3-6m sprint	7.11 (0.61)	6.98 (0.62)	0.14 (0.38)	0.80	0.58	0.91	0.28	0.75
Test8	3-3-6m rotation (left)	8.05 (0.74)	7.92 (0.81)	0.13 (0.36)	0.88	0.74	0.95	0.26	0.70
Test9	3-3-6m rotation (right)	8.06 (0.88)	7.82 (0.72)	0.24 (0.48)	0.79	0.53	0.91	0.37	0.94
Test10	90°- 90° turn on the spot with stop (left)	1.49 (0.26)	1.40 (0.18)	0.09 (0.19)	0.62	0.28	0.82	0.14	0.37
Test11	12 m dribble	6.23 (0.68)	6.19 (0.60)	0.04 (0.45)	0.76	0.51	0.89	0.31	0.88
Test12	12 m rotation dribble (right)	8.29 (1.31)	8.34 (1.20)	-0.05 (0.81)	0.80	0.59	0.91	0.56	1.58
Test13	12 m rotation dribble (left)	8.30 (1.06)	8.24 (1.04)	0.06 (0.74)	0.76	0.52	0.89	0.51	1.44
Test14	90°- 90° turn on the spot with stop (right)	1.40 (0.20)	1.36 (0.16)	0.04 (0.16)	0.62	0.30	0.82	0.11	0.31
Test15	Combination	14.44 (1.30)	14.41 (1.13)	0.04 (0.49)	0.92	0.83	0.97	0.34	0.96
<b><i>Overall performance time</i></b>		82.88 (7.22)	82.31 (6.41)	0.57 (2.14)	0.95	0.89	0.98	0.98	4.20

## Discussion

This study describes the development of a new field-based WMP test to assess the capacity of mobility performance and its construct validity and test-retest reliability. To examine the construct validity, we hypothesized that classification, playing standard and sex will influence the performance on the test. The construct validity tests showed that the WMP test distinguishes sex and playing standards, but did not show differences between low and high classifications on the overall performance time. The test-retest reliability for the overall performance time was excellent and an improvement of 4.2s (5.1%) can be detected relative to the overall performance time. However, the reliability for the activities related with rotation on the spot and the 12 m sprint is low.

### *Test development*

The WMP test which is introduced in this article is a simulation of mobility performance during matches specific to wheelchair basketball. The WMP test can easily be used by trainers, coaches and scientists to gain insight into the capacity of mobility performance of players. The developed WMP test meets the requirements which have been reported in previous studies of wheelchair court sports (Goosey-Tolfrey & Leicht, 2013; Mason et al., 2013; Vanlandewijck, Theisen, & Daly, 2001). The WMP test is based on the most common aspects of mobility performance, the players are tested in their natural environment and they are tested with their own wheelchair configuration. However, mobility performance may change when essential aspects of the sport change, e.g. changes in the basketball rulings or wheelchair regulations. In the case of such changes, the mobility performance needs to be redefined.

### *Construct validity*

Players with a high classification ( $\geq 3.0$  points) are expected to perform better than players with a low classification ( $\leq 2.5$  points) (van der Slikke et al., 2015b; Vanlandewijck et al., 1999). The key determinants of the classification system are the ability to have active stability and rotation possibilities of the trunk. Previous research shows that trunk impairment had impact on wheelchair propulsion, especially in accelerating from standstill (Chow et al., 2009; Vanlandewijck et al., 2001). The overall performance time of the WMP test showed a borderline non-significant difference ( $p=0.06$ ) and a moderate ES in capacity of mobility performance between low and high classifications. There were significant differences between classification levels on the separate activities related to driving forward movements (no. 3, 7 and 15). In contrast, almost all activities related to rotational movements of the wheelchair showed no significant differences, which could mean that classification (trunk impairment) has less influence on rotational movements. Furthermore, the used cut-off point for dichotomizing classification in this study is debatable. Other studies showed differences between classification 1 (and 1.5) point players compared to the other classifications (Mokkink et al., 2010; Vanlandewijck et al., 1995; Vanlandewijck et al., 2003). Currently, there is not a clear

relationship between classification and mobility performance. The impact and content of the classification system should be further investigated in future research.

The second hypothesis was that players competing at an international playing standard perform better than players at a national standard. This hypothesis proved to be true for the overall performance time and for 12 of the 14 separate activities with moderate-to-large ES (0.81-1.72). Except three activities related with turn on the spot, players at an international standard perform all the activities faster than national standard players. The difference between national and international playing standard on the overall performance time was 8.11s, which is significantly more than the LoA calculated in the reliability study (4.20s). Although the findings are in line with the hypothesis, the differences may be partly explained by other factors than the actual capacity of the athletes in mobility performance. Possibly, due to the more professional approach, international players may have a more optimized wheelchair configuration compared to national players which might have affected their performance on the test circuit. The activities, which showed no differences between playing standards were again related with turn on the spot. These activities are, in addition to low reliability, not distinctive for playing standards. Turns on the spot are frequent elements of performance during matches and, therefore, important to include in the WMP test. However, time appears not to be a reliable outcome measure for these activities. In order to optimize the test, these activities must be further examined. At the moment, the WMP test is also analysed with data from inertial sensors using the method of van der Slikke et al. (van der Slikke et al., 2015) with outcome measures such as velocity and acceleration.

The third hypothesis was that men perform better at the WMP test than women of the same playing standard. Except, again, for the activities related with turn on the spot, the hypothesis proved true. Men did perform all activities faster than women, except for the 12-m sprint with ball possession. The hypothesis is based on differences in upper body strength and trunk stability between men and women (Gómez et al., 2014). However, for the 12-m sprint with ball possession ball-handling skills play an important role. For the rotational movement combined with ball possession the hypothesis was proven. It may be possible that there is a difference in training focus between the international men and women in ball handling. Women may have better ball skills and with this they compensate for their slower performance on the 12-meter sprint.

In this study three hypotheses were formulated and tested to determine the construct validity of the WMP test. These hypotheses are chosen based on literature and practical feasibility. Several other variables than classification, gender and sex could have an influence on the mobility performance. Examples of variables which may also could have been used are floor surface and wheelchair configurations aspects such as wheel size, camber and elbow angle. Floor surface can affect performance due to a different rolling resistance and the WMP test should reveal this difference. However, for the present study it was practically difficult to



organize to have players perform the test circuit at different floor surface. In addition, it should be mentioned that other variables than mentioned in the hypothesis might have partly affected the differences in mobility performance. In this study we focused primarily on the construct validity of the WMP test and not at variables that best predict performance on the WMP test.

### *Reliability*

The ICC values of the separate activities of the WMP test ranged between 0.25 and 0.95, and 5 of the 15 outcome measures showed low reliability (<0.70). The ICC of four activities that included a turn on the spot ranged between 0.25 and 0.62. The performance time of these activities is very short compared to the other activities. For example, the average duration for a turn of the spot (left) is 0.90s with SEM of 0.1s. The reason for these lower ICC values could be that the measurement error of these activities is relatively high due to the short performance times. Because of this, performance time may not be an adequate outcome parameter in these four activities. In this study, the reliability between the WMP test and retest on the 12-m sprint time was also low (ICC=0.62). Previous research showed that time over a 15-m sprint cannot be used to assess wheelchair-specific capacity (Van der Scheer, Jan W, de Groot, Vegter, Veeger, & van der Woude, Lucas HV, 2014). In contrast, de Groot et al. (2012) reported a good reliability score (ICC 0.80 – 0.84) for a 5-m sprint test. These differences in reliability could be explained by the differences in handling the timing of deceleration to stop. In our study the players had to stand still at the end of the 12-m while in the study of de Groot et al. (2012) the players were allowed to drive over. The potential large variation between and within participants in timing of starting to decelerate and the level of braking (hand) forces needed to stand still at 12-m may have resulted in a relatively large variation of performance time and thus a low reliability score. The ICC of the 12-m sprint with stops is 0.80 and well in line with the study of de Groot et al. (2012). The 12-m sprint with stops is in this case divided in three short sprints of 3, 3 and 6 m, and thus comparable in distance with the (single) 5 m in the study of de Groot et al. (2012). Although the total distance of the sprints with and without stops is the same, the inclusion of starts from stand still and stops seems to affect reliability. However, the design of the 12-m sprint as part of the WMP test, including the acceleration and deceleration phases, is in our opinion an essential element of mobility performance, also considering the results of the observations of wheelchair basketball matches (de Witte et al., 2016).

### *Limitations*

All athletes performed the test in their own sports wheelchairs. Each wheelchair is individually adjusted in order to achieve an optimal wheelchair-athlete interaction. Although wheelchair configuration affects mobility performance, we do not expect this have biased our conclusions regarding validity and reliability of the WMP test because of the relatively large within groups variability in wheelchair configurations. In addition, the choice to measure wheelchair

basketball players in their own environment and wheelchair enhanced the external validity of the study. Another limitation of this study is the missing data of activity 1 (tik-tak box) for which, in future research, the video set-up must be examined.

#### *Conclusion and practical implications*

It can be concluded that the construct validity and reliability of the WMP test were good for the overall performance time score. The test can be used as a standardized mobility performance test to assess the capacity of mobility performance of elite wheelchair athletes in wheelchair basketball. In addition, novice players might use the test to achieve a higher level of mobility performance and monitor their progression in mobility performance aspects related to elite wheelchair basketball. The overall outcome of the WMP test is reliable. However, the activities related with turn on the spot (no. 2,6,10 & 14) show low reliability and construct validity.

The WMP test can be easily used to periodically monitor the capacity of wheelchair basketball players in mobility performance. The test results can be used to detect strengths and weaknesses of players in different aspects of mobility performance. For example, when a player performs driving forward actions significantly better than rotation actions -compared with team mates- the trainer can use these outcomes to develop specific training schemes. In addition, the test can be used to monitor the progress in mobility performance, to detect talented athletes and to examine whether an athlete is sufficiently recovered from an injury. For research purposes, we aim to use this WMP test to examine the impact of different wheelchair configurations on mobility performance, as recommended by Mason et al. (2013).



# Chapter 6

## The future of classification

The future of classification in wheelchair sports; can data science and technological advancement offer an alternative point of view? *International Journal of Sports Physiology & Performance*



## Chapter 6: The future of classification

### The future of classification in wheelchair sports; can data science and technological advancement offer an alternative point of view?

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#### Abstract

**Purpose:** Classification is a defining factor for competition in wheelchair sports, but it is a delicate and time-consuming process with often questionable validity. (Tweedy & Vanlandewijck, 2011) New inertial sensor-based measurement methods applied in match play and field tests, allow for more precise and objective estimates of the impairment effect on wheelchair mobility performance. It was evaluated if these measures could offer an alternative point of view for classification. **Methods:** Six standard wheelchair mobility performance outcomes of different classification groups were measured in *match* play (n=29), as well as *best* possible performance in a field test (n=47). **Results:** In *match*-results a clear relationship between classification and performance level is shown, with increased performance outcomes in each adjacent higher classification group. Three outcomes differed significantly between the low and mid-class groups, and one between the mid and high-class groups. In *best* performance (field test), a split between the low and mid-class groups shows (5 out of 6 outcomes differed significantly) but hardly any difference between the mid and high-class groups. This observed split was confirmed by cluster analysis, revealing the existence of only two performance-based clusters. **Conclusion:** The use of inertial sensor technology to get objective measures of wheelchair mobility performance, combined with a standardized field-test, brought alternative views for evidence-based classification. The results of this approach provided arguments for a reduced number of classes in wheelchair basketball. Future use of inertial sensors in match play and in field testing could enhance evaluation of classification guidelines as well as individual athlete performance.

**Keywords:** *Paralympic sports, wheelchair basketball, classification, , inertial sensors, big data*

## Introduction

In most Paralympic sports, a classification system is used to attain fair competition between athletes with various levels of impairment. The Paralympic classification systems aims to promote sports participation of people with disabilities by minimizing the impact of eligible types of impairment on competition outcome (Tweedy & Vanlandewijck, 2011). Ideally, the classification should only cover the effect of impairment on game performance. Evidently, the magnitude of that effect is hard to estimate accurately given the number of confounding factors (Vanlandewijck et al., 2004). To determine the level of impairment itself, most classification systems categorize based on function levels rather than on pathology (Pickering Francis, 2005). Functional assessment is either based on isolated function tests, with assumptions about their effect on game performance, or the classification system is based on match observation. Given the diversity of functions, it is nearly impossible to determine the effect of each impairment level on game performance. The latter argument pledges for the use of match observation-based classification, but for those systems match related confounders (field position, opponent, tactics) affect the functional assessment.

Wheelchair basketball was the first disability sport to use a functional classification system. Although functional classification is now a common practice, the wheelchair basketball system still stands out since the function level assessment is based on match observation of “volume of action”, instead of isolated function tests. The wheelchair basketball classification system (IWBF; [www.iwbf.org](http://www.iwbf.org)) started out as a medical based system (3 classes), but with the conversion to a function-based system, the number of classes was extended to 8, in order to take the increasing heterogeneity of participants into account. Classifications range from 1 (most impaired) to 4.5 points (no functional limitation), with a team of five athletes composed of maximal 14 points. Although used since 1982, (DePauw, 1995) there is an ongoing quest to provide scientific knowledge for more evidenced based classification guidelines (Altmann, Hart, Vanlandewijck, van Limbeek, & van Hooff, 2015; Vanlandewijck et al., 1995; Vanlandewijck et al., 2004). The advantage of a match observation-based classification is that the assessments are made in an ecologically valid way, but observation methods also have their flaws and limitations. Actions like ball handling are well observed, but estimations of speed, acceleration and force, cannot be assessed accurately on observation alone. Another contaminating factor in the current observations is that match specific factors like field position (guard, forward, centre), opponent and coach instructions are known to interact on performance (Vanlandewijck et al., 2004). Indeed, more impaired players (low classification) are often positioned in physically less demanding field positions, possibly masking their potential best performance levels. Therefore, assessment of performance in a match alone provides a narrowed image, possibly disregarding best possible performance levels. On the other hand, testing best performance in an isolated field test or lab setting alone, does not provide information on how well an athlete is able to make use of his performance capacities during the course of a match. Therefore, research on the relationship between *match* and *best*

condition is needed to determine if measurements in only one condition are sufficient for well-founded classification.

Several researchers investigated the effect of impairment on performance as expressed in the current classification, both in *match* conditions as well as in a field test to measure *best* possible performance. Vanlandewijck et al. (1995) assessed the wheelchair basketball performance of differently classified players during a match based on the Comprehensive Basketball Grading System (CBGS), next to the physical fitness in a laboratory test. Based on their results they considered a reduced number of classes viable. In a similar study by Vanlandewijck et al. (2004) based on the CBGS scores of match performance, the relationship between class and position in the field was appointed as one of the factors for the absence of significant performance differences between two adjacent classes. In a study by Molik et al. (2013) a Wingate Anaerobic Test was used to assess indexes of upper extremity anaerobic performance, which also led to the conclusion that a reduced number of classes was recommendable. So, in research a relationship between classification and different performance measures is acknowledged in various conditions. Yet, to identify the true effect of impairment on performance and to explore the relationship between *match* and *best* performance, a single outcome measure should be used in both conditions.

A recently introduced method based on inertial sensors, allows for objective performance estimations in both *match* and *best* condition, in a reliable and unobstructive way (van der Slikke et al., 2015). This method quantifies the *wheelchair mobility performance*, that is the ability to manoeuvre the wheelchair. This measure for the combined wheelchair-athlete combination is one of the most important performance aspects (Mason et al., 2013) contributing to the overall game performance as described by Byrnes et al. (1994). In elite wheelchair basketball, van der Slikke et al. (2016) confirmed the clear relationship between classification and wheelchair mobility performance, but so far only in *match* conditions not yet in *best* conditions (field test). In this study, wheelchair basketball athletes were measured in a sport specific wheelchair mobility performance field test (de Witte et al., 2017), that was first tested for reliability. Once the reliability had been ascertained, forty-seven elite athletes of all classifications were tested for *best* wheelchair mobility performance in this field test, to rule out possible *match* related confounding factors on wheelchair mobility performance.

The present study explores the relationship between wheelchair mobility performance in both *match* and *best* condition and its interaction with classification. The current classification is then compared to clusters derived from wheelchair mobility performance analysis in *best* conditions, to outline a suitable number of performance based classes. Finally, we will evaluate whether such clustering may provide an alternative point of view to classification systems.

## Methods

### Subjects

Wheelchair mobility performance was measured in a match (van der Slikke et al., 2016) for the first group of elite wheelchair basketball athletes (n=29) and in a standardised field test for a second group of athletes (n=47, Table 6.1). Part of the athletes (n=12) were measured in both conditions, forming a third dataset for analysis of the relationship between match and field test performance. For the purpose of reliability testing, twenty-three of the athletes performed the field test twice. Results of this test-retest analysis are described in Appendix II. This study was approved by the ethical committee of the department of Human Movement Sciences: ECB-2014-2. All participants signed an informed consent after being informed on the aims and procedures of the experiment.

**Table 6.1: The distribution of classification and age (years) per competition level group of athletes measured in the field test.**

Level		Mean	SD	Classification						
				1.0	1.5	2.0	2.5	3.0	4.0	4.5
National Male (NM)	Class	3.3	1.2	2	1	1	1	2	7	4
	Age	23.7	10.1							
International Male (IM)	Class	3.0	1.2	2	1	1	4	3	2	4
	Age	26.4	7.8							
International Female (IF)	Class	2.8	1.2	1	2	1	2	3	1	2
	Age	32.9	8.0							
Total				5	4	3	7	8	10	10
Group total				Low = 9		Mid = 18		High = 20		

### Methodology

Each athlete's own sports wheelchair was equipped with three inertial sensors (xIMU for match, X-IO technologies; Shimmer3 for field test, Shimmer Sensing, Figure 6.1), one on each rear wheel axis and one on the rear frame bar. The frame sensor was used for measuring forward acceleration as well as rotation of the frame in the horizontal plane (heading direction). The combined signals of wheel sensor acceleration and gyroscope were used to estimate wheel rotation, which in turn provided frame displacement given the wheel circumference.

Estimates of frame rotations in the horizontal plane were used to correct the wheel gyroscope signal for wheel camber angle, as described by Pansiot et al. (2011), Fuss et al. (2012) and van der Slikke et al. (2015). Furthermore, a skid correction algorithm was applied to reduce the effect of single or concurrent wheel skidding (van der Slikke et al., 2015a).





Figure 6.1: Measurement setup, with inertial sensors on wheels and frame and measurements during a match. (Photograph by [www.frankvanhollebeke.be](http://www.frankvanhollebeke.be)).

Based on inertial sensor outcomes for each measurement a wheelchair mobility performance plot was generated, showing the six key outcomes of wheelchair performance (van der Slikke et al., 2016). The outcomes included are: average speed; average best speed (of best 5 in a match and of best 2 in the field test); average acceleration in the first 2m from standstill; average rotational speed during forward movement; average best rotational speed during a turn on the spot (of best 5 in a match and of best 2 in the field test) and average rotational acceleration.

#### *Statistical analysis*

To test for classification effects on wheelchair mobility performance, athletes were split into three classification groups: low (1 -1.5), mid (2 – 3) and high (4 – 4.5). These classification group boundaries were chosen in line with earlier research regarding wheelchair mobility performance. In the paper by van der Slikke et al. (2011) they chose to separate the class I (1 – 1.5) in a single group, given their distinct performance levels 2,5 and to separate class IV (4 -4.5) from the class II & III athletes, since they also show (to a lesser extent) distinct performance levels (Vanlandewijck et al., 1995; Vanlandewijck et al., 2004). Visual inspection of the distribution, followed by a Kolmogorov-Smirnov test was applied to test for normal distribution (Ghasemi & Zahediasl, 2012) of all six wheelchair mobility performance outcomes, to verify for the use of parametric statistics. A one-way ANOVA was used to test for group differences in the six standard mobility performance outcomes. For both field test (n=47) and match data (n=29), post-hoc Bonferroni tests were applied to identify between which groups significant differences occurred (Field, 2013). The magnitudes of the classification group differences in the field test were also expressed in the Smallest Detectable Difference (SDD 95%) as determined by the test-retest reliability (appendix II). For the 12 athletes measured in both field test and match, a Pearson correlation was calculated for all six outcomes of the wheelchair mobility performance, combined with a paired samples T-Test to verify if there were structural differences.

TwoStep clustering analysis was applied (Bacher, Wenzig, & Vogler, 2004; Fraley & Raftery, 1998; Mooi & Sarstedt, 2010) to the complete field test performance dataset, without the split in classification groups (appendix III). The TwoStep method is an exploratory tool designed to reveal natural groupings within a dataset that would otherwise not be apparent (Chiu, Fang, Chen, Wang, & Jeris, 2001). Given the small sample size, a log-likelihood distance measure was used combined with the Schwartz's Bayesian Criterion (Schuetz, 2011). Since the maximal number of clusters is arbitrary, it was set in alignment to the current classification system (n=8).

### Results

For the twenty-nine athletes measured in match play, classification group averages are displayed in the standardized wheelchair mobility performance plot (Figure 6.2, van der Slikke et al., 2016). The plot range was slightly enlarged to allow display of the best wheelchair mobility performance outcomes per classification group of the forty-seven athletes measured in the field test (Figure 6.3).

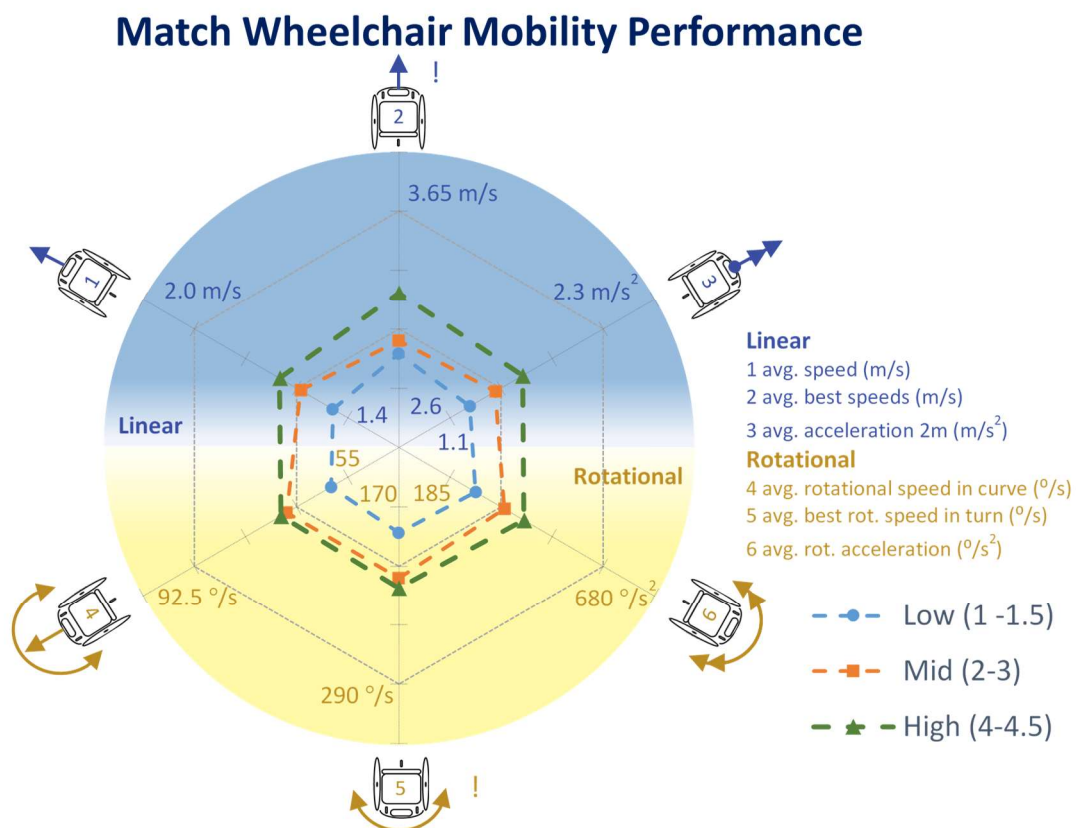


Figure 6.2: Wheelchair mobility performance in a match for three classification groups, adapted from van der Slikke et al., 2016.

## Field test Wheelchair Mobility Performance

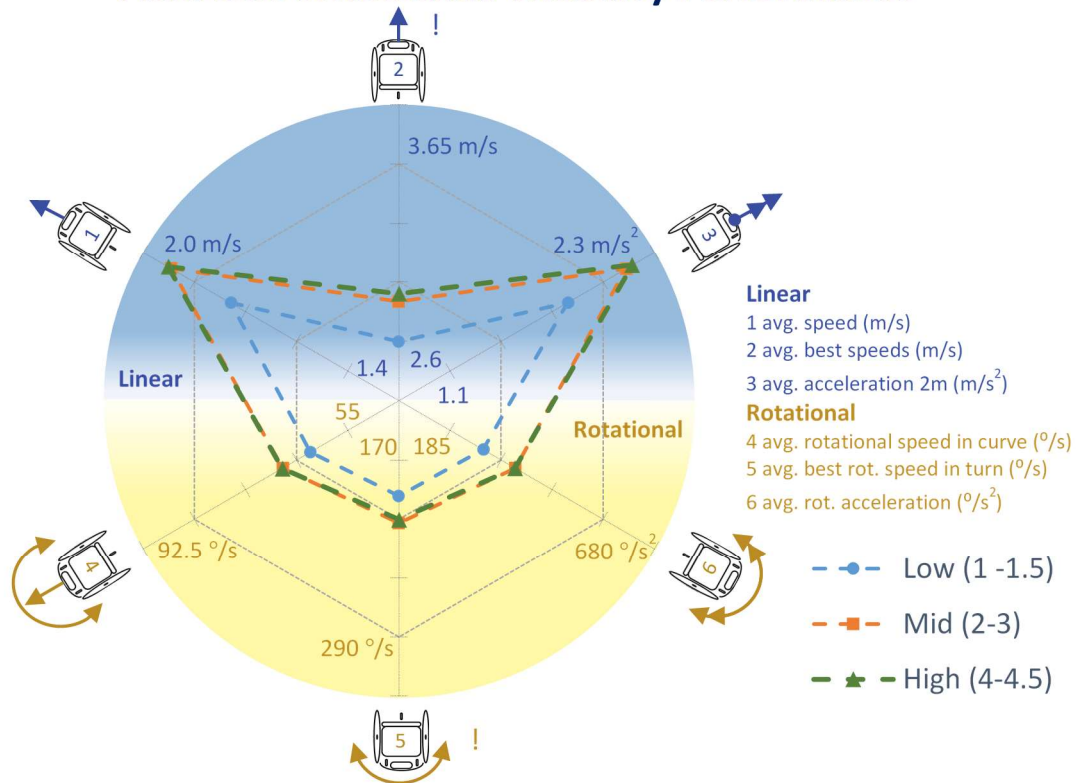


Figure 6.3: Best possible wheelchair mobility performance as measured in the field test for three classification groups.

The differences of wheelchair mobility performance outcomes in the field test are also expressed in a factor of the SDD 95% (Table 6.2). The lowest factors of SDD 95% appear between the mid and high classification group (0 -1.0) and the highest factors show between the low and high classification group (1.3-6.5).

Table 6.2: Classification group differences in the field test expressed as a factor of the Smallest Detectable Difference (SDD, see Appendix I).

	SDD 95%	Low - Mid	Low - High	Mid - High
Forward speed avg. (m/s)	0.038	<b>6.2</b>	<b>6.5</b>	0.3
Forward speed best (m/s)	0.046	<b>5.2</b>	<b>6.2</b>	1.0
Forward acceleration avg. (m/s <sup>2</sup> )	0.085	<b>5.3</b>	<b>6.0</b>	0.6
Rotational speed curve avg. (°/s)	3.409	<b>2.0</b>	<b>2.0</b>	0.0
Rotational speed turn best (°/s)	12.065	<b>1.5</b>	<b>1.3</b>	0.2
Rotational acceleration avg. (°/s <sup>2</sup> )	18.740	<b>5.5</b>	<b>5.5</b>	0.0

Notes: Factors of SDDs over 1 are marked bold

Classification groups showed significant ( $p < 0.05$ ) differences in all six wheelchair mobility performance outcomes in the match and in 5 in the field test measurements (Table 6.3). Post-hoc Bonferroni tests revealed that in the *match* 3 out of 6 outcomes differed significantly ( $p < 0.05$ ) between the low and mid classified athletes and only best forward speed differed

between the mid and high classified group (Table 6.3). For *best* performance as measured in the field test, five wheelchair mobility performance outcomes differed significantly between low and mid classified athletes and no outcomes differed between mid and high classified athletes.

**Table 6.3: Classification group statistics in the match and field test data.**

	Match				Field Test			
	ANOVA	Bonferroni post-hoc			ANOVA	Bonferroni post-hoc		
		Low - High	Low - Mid	Mid - High		Low - High	Low - Mid	Mid - High
Forward speed avg. (m/s)	<b>0.000</b>	<b>0.000</b>	<b>0.021</b>	0.214	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	1.000
Forward speed best (m/s)	<b>0.000</b>	<b>0.000</b>	0.993	<b>0.003</b>	<b>0.000</b>	<b>0.000</b>	<b>0.003</b>	1.000
Forward acceleration avg. (m/s <sup>2</sup> )	<b>0.001</b>	<b>0.001</b>	0.139	0.105	<b>0.003</b>	<b>0.003</b>	<b>0.010</b>	1.000
Rotational speed curve avg. (°/s)	<b>0.002</b>	<b>0.004</b>	<b>0.007</b>	1.000	<b>0.009</b>	<b>0.012</b>	<b>0.016</b>	1.000
Rotational speed turn best (°/s)	<b>0.003</b>	<b>0.004</b>	<b>0.013</b>	1.000	0.068	0.146	0.078	1.000
Rotational acceleration avg. (°/s <sup>2</sup> )	<b>0.006</b>	<b>0.005</b>	0.115	0.443	<b>0.002</b>	<b>0.003</b>	<b>0.004</b>	1.000

**Notes:** Significance levels are shown, with all levels  $p < 0.05$  marked bold. Result description is based on adjacent class groups, that is between low-mid and between mid-high. Differences between the low and high classified athletes are obvious and not used in further interpretation of results.

For the twelve athletes measured in both match and field test conditions, the Pearson correlations for all six wheelchair mobility performance outcomes are displayed in Table 6.4. Three outcomes were significantly ( $p < 0.05$ ) higher in the field test compared to the match performance, and two outcomes were higher on average, but not significant. The average best speed was significantly lower in the test compared to the match performance.

**Table 6.4: Pearson correlation and mean differences between match and field test performance (n=12);**

	Pearson correlation	Mean diff.	p value T-Test
Forward speed avg. (m/s)	<b>0.735</b>	0.42	<b>0.000</b>
Forward speed best (m/s)	<b>0.756</b>	-0.19	<b>0.001</b>
Forward acceleration avg. (m/s <sup>2</sup> )	<b>0.702</b>	0.92	<b>0.000</b>
Rotational speed curve avg. (°/s)	<b>0.721</b>	1.70	0.221
Rotational speed turn best (°/s)	0.616	0.60	0.936
Rotational acceleration avg. (°/s <sup>2</sup> )	<b>0.745</b>	64.0	<b>0.002</b>

**Notes:** all Pearson correlations were significant ( $p < 0.05$ ),  $> 0.7$  marked bold; if match performance exceeds test outcomes, a negative value is shown in the mean difference; significance levels  $< 0.05$  in the T-test are marked bold.

The TwoStep analysis revealed two clusters, from a model that was considered “good” based on the cluster quality (silhouette of cohesion and separation  $\geq 0.5$ ). Most important model predictors were all forward movement based outcomes (factor 0.93 – 1), whereas the importance of rotational outcomes ranged from a factor 0.35 - 0.51. If analysed for class allocation (Table 6.5), the first cluster (A) shows clear agreement with the low classified group,

although 6 athletes of the higher-class groups are included as well. The second cluster (B) corresponds very well to the mid/high classified groups, with only one athlete of the low-class group included. The differences in performance outcomes between clusters, as expressed in the factor of SDD 95%, are quite similar to the ones shown between classification groups (low-mid & low-high, Table 6.2).

**Table 6.5: The TwoStep clustering method applied to the dataset of the 47 athletes measured in the field test revealed two clusters (A & B). The table shows the distribution of athlete’s classification over the two clusters. cluster performance characteristics and their differences.**

Class	Cluster		mean diff	Factor SDD 95%	p value T-Test
	A	B			
Low	8	1			
Mid	4	14			
High	2	18			
Total	14	33			
Forward speed avg. (m/s)	1.87	2.13	0.26	6.83	<b>0.000</b>
Forward speed best (m/s)	2.60	2.90	0.30	6.51	<b>0.000</b>
Forward acceleration avg. (m/s <sup>2</sup> )	1.97	2.60	0.63	7.37	<b>0.000</b>
Rotational speed curve avg. (°/s <sup>2</sup> )	64.5	71.9	7.4	2.16	<b>0.000</b>
Rotational speed turn best (°/s <sup>2</sup> )	193.9	213.9	20.0	1.66	<b>0.001</b>
Rotational acceleration avg. (°/s <sup>2</sup> )	307.3	404.7	97.4	5.20	<b>0.000</b>

**Notes:** If optimized for group size (most athletes per class in each cluster), there is a clear split (dashed line) between the low and mid/high classification groups. The lower part of the table shows the wheelchair mobility performance outcomes per cluster and their difference, also expressed as a factor of the SDD 95% (Appendix I).

## Discussion

This study was aimed at exploring the relationship between *match* and *best* wheelchair mobility performance and to what extent that relationship is affected by impairment level as expressed in the current classification. In general, it is clear that wheelchair mobility performance is clearly affected by the athlete’s impairment level. This effect is shown in the *match* results, with increased performance outcomes for each successive classification group. Of the six wheelchair mobility performance outcomes, three differ significantly between the low and mid-class group and one between the mid and high-class group. Once the *match* related factors are expelled, a different pattern emerges as shown by the *best* results (field test measurements). Rather than a gradual incline of performance with classification (Figure 6.2), a clear performance separation shows with the most prominent difference between low and mid-class group outcomes. The wheelchair mobility plot (Figure 6.3) neatly shows that in the field test, only the low-class group deviates from the performance of the other athletes. Five of the wheelchair mobility performance outcomes differed significantly between these class groups, whereas no significant differences showed between mid and high classified athletes.

A relationship between classification and wheelchair mobility performance was anticipated in *match* and *best* condition. Indeed, low-class athletes show the lowest performance outcomes

and high-class athletes the highest wheelchair mobility performance values in both conditions, but the patterns of mid-class athletes differ between conditions. So only moderate correlations between *match* and *best* performance were expected due to those differences in the mid-class group. Moderate to high correlations (0.62-0.76) showed for the performance of the twelve athletes measured in both conditions. Given the unrestrained nature of the field test (no opponent or other obstructions), it was anticipated that wheelchair mobility outcomes would equal or exceed those of match conditions. Indeed, three out of six outcomes were significantly higher in that condition. Only average best speed appeared to score significantly lower in the field test. In the field test, the longest continuous run is 12-meter, where in a match -although not frequent- longer continuous runs occur, with corresponding higher speeds.

The impairment effect on performance should shape the classification system, so the International Paralympic Committee (IPC) is committed to the development of selective classification systems, not performance classification systems (Tweedy & Vanlandewijck, 2011). It is vital that athletes who improved their performance by training are not competitively disadvantaged by being placed into a less impaired class. Nevertheless, since performance level seems more dominated by impairment level rather than athlete training status or competition level (van der Slikke et al., 2016), performance clusters could be used to outline the number of classes needed in a particular system.

Once extracted from the *match* specific confounders, field test wheelchair mobility performance data could be enforced to argue for a reduced number of classifications. Based on TwoStep clustering, only two performance clusters appeared. In clustering, outcomes related to forward speed and acceleration showed to be dominant factors. The two clusters show much similarity with the current classification of athletes, with only one athlete of the low-class group assigned to cluster B. The remaining athletes of the low classified group were assigned to cluster A, but this cluster also comprised four athletes of the mid-class and two of the high-class group. In the population measured, athletes from both international and national competition level were included. The mid and high classified athletes assigned to cluster A were national males (n=4) and international females (n=2). In future research, a more homogenic group of athletes regarding competition level might slightly alter TwoStep cluster analysis outcomes.

Only regarding wheelchair mobility performance, a single separation between the current class 1-1.5 athletes and the rest would be adequate. Subsequently, the 2+ class athletes could be divided into two groups given the effect of their impairment regarding ball handling. Such a reduced number of classes is in line with the conclusion of Vanlandewijck et al. (1995) and Molik et al. (2013), pinpointing the viability of a reduction in the number of classes. A reduction in classes is also in line with the idea that the range of activity limitation within a class should also be as large as possible without disadvantaging those most severely impaired (Tweedy & Vanlandewijck, 2011). The wheelchair basketball specific field test used, is more closely related

to match mobility performance than general performance measures (such as a physical fitness test or Wingate Anaerobic test) frequently used in earlier research, so it provides more match specific functional outcomes.

The aim of this study was to provide insight in the relationship between impairment and mobility performance in both *best* and *match* condition, and to demonstrate the additional value of objective measures as provided by new technologies. Although the current classification system functions, with athletes and coaches generally satisfied (Molik et al., 2017), there still remains some controversy about the best approach to determine function level. The International Wheelchair Basketball Federation does not want to discard a reasonable well-functioning classification system based on years of gradual improvement, whereas the IPC seeks unity in systems over all sports, with selective classification based on “physical and technical assessment” off court. Given that aspiration, the wheelchair mobility performance method used in this research seems unsuitable as a direct classification tool. Still, the need for sport specific test batteries to aid the classifiers in objective decision making is emphasised by Tweedy et al. (2011). They state that current classification systems are still based on the judgement of a small number of experienced classifiers, rather than on empirical evidence, making the validity of the systems often questionable. In wheelchair basketball, the classification method is also time consuming and complicated. The use of objective measurement methods and sport specific field tests can aid classifiers in their decision making. Results of the present study show the significance of on court mobility performance measurements, whereas the ease of use of the inertial sensor-based method enables big scale measurements in the future. By using the same method in both conditions, results of continued measurements in *match* play will also approximate *best* performance (field test), reducing the effect of random factors typical to the observation of only a few matches as in the classification current system. Indeed, it also brings to light whether athletes intentionally show a misrepresentation of their abilities in the classification tests, a major issue in Paralympic sports.

#### Practical Applications

The wheelchair basketball specific field test used in this study (de Witte et al., 2017), proved to be reliable combined with the inertial sensor-based method for measuring wheelchair mobility performance. In that sense, it complies to the IPC appeal to develop sport specific test batteries for classification support. Next to use for classification support, the field test is also a useful tool for individual athletes and coaches. Given the magnitudes of the smallest detectable differences for all 6 outcomes, the field test is expected to be sensitive enough to detect performance changes as a result of training or interventions regarding wheelchair settings. Additional body fixed inertial sensors could be used for more profound insight in the relationship between body movement (“volume of action”) and wheelchair mobility performance.

## Conclusion

Technological advancement, especially application of inertial sensors, allows for easy to use, large scale, objective and increasingly precise measurement of performance. Those benefits enable data science in adapted sports research that is traditionally characterized by small participant numbers. Such a big data approach with continued measurements in all conditions might offer an alternative point of view for classification outlining in Paralympic sports. Future research with additional body fixed inertial sensors might reveal more insight in the relationship between impairment and performance, bridging the gap to the selective classification envisioned by the IPC.

## Acknowledgement

The authors would like to thank all athletes participating in this research project, all coaches involved in measurement planning, Yves Vanlandewijck, Kees van Breukelen and Frank van der Meulen for their contribution to this research and manuscript.

## Conflict of interest statement

None.

## Appendix I

The athlete's performance can be divided in physical performance, mobility performance and game performance. Physical performance only concerns the athlete (Bloxham et al., 2001), whereas mobility performance is the measure for the combined wheelchair-athlete combination (Mason et al., 2013). Therefore, although mobility performance is established by athlete exertion, it is often expressed in terms of wheelchair kinematics. Van der Slikke et al. (2016) used a set of three inertial sensors to measure the wheelchair kinematics of 29 athletes in wheelchair basketball match play. To reduce the vast number of kinematic outcomes that could be measured with this configuration, principal component analysis was used to extract a set of six key features describing wheelchair mobility performance characteristics. Three of these outcomes describe forward motion and three describe the rotational aspect (manoeuvrability). All outcomes are plotted in a radar plot, with a scale relative to the group average and standard deviation.

## Appendix II

Reproducibility of wheelchair mobility performance outcomes in the field test was tested by measuring 23 male athletes twice (de Witte et al., 2017). Re-tests were performed one week after, under the same conditions (same timeframe, day of the week and same location). For each of the six performance outcomes the Intra Class Correlation coefficient for consistency (ICCc) between test and re-test was calculated (Table 6.6). Based on the ICCc value and Standard Deviation (SD), the Standard Error of Mean for consistency (SEM<sub>c</sub>) and the Smallest Detectable Difference (SDD 95%) were calculated using:

$$SEM_c = SD * \sqrt{(1 - ICC_c)}$$



$$SDD\ 95\% = SEM_c * \sqrt{2} * 1.96$$

The SDD 95% for each of the six performance outcomes is used to describe the differences between average performance of classification groups. For each outcome, the difference is divided by the SDD 95%, resulting in a dimensionless factor.

**Table 6.6: ICC, SEM and SDD 95% of wheelchair mobility performance outcomes measured twice in the standardized field test.**

	ICC	SD	SEM	SDD 95%
Forward speed avg. (m/s)	<b>0.947</b>	0.059	0.014	0.038
Forward speed best (m/s)	<b>0.947</b>	0.072	0.016	0.046
Forward acceleration avg. (m/s <sup>2</sup> )	<b>0.950</b>	0.138	0.031	0.085
Rotational speed curve avg. (°/s)	0.870	3.41	1.23	3.41
Rotational speed turn best (°/s)	0.837	10.78	4.35	12.07
Rotational acceleration avg. (°/s <sup>2</sup> )	<b>0.944</b>	28.57	6.76	18.74

### Appendix III

The TwoStep Cluster Analysis procedure is an exploratory tool designed to reveal natural groupings (or clusters) within a data set that would otherwise not be apparent. It has several unique features that makes it very versatile. The most important feature for application in this study is the fact that it is capable of automatic selection of the number of natural clusters.

The two steps can be summarized as follows: Step 1) The procedure begins with the construction of a Cluster Features (CF) Tree. The tree begins by placing the first case at the root of the tree in a leaf node that contains variable information about that case. Each successive case is then added to an existing node or forms a new node, based upon its similarity to existing nodes and using the distance measure as the similarity criterion. A node that contains multiple cases contains a summary of variable information about those cases. Thus, the CF tree provides a capsule summary of the data file. Step 2) The leaf nodes of the CF tree are then grouped using an agglomerative clustering algorithm. The agglomerative clustering can be used to produce a range of solutions. To determine which number of clusters is "best", each of these cluster solutions is compared using the Schwarz's Bayesian Criterion (BIC).

In this study, for each of the forty-seven athletes, six wheelchair mobility performance outcomes are included in the dataset for clustering. The TwoStep clustering procedure reveals the number of natural clusters and the assignment of each athlete to a cluster. To quantify the "goodness" of a cluster solution, the silhouette coefficient is used. This coefficient indicates how well the elements within a cluster are similar to one (cohesive) while the clusters themselves are different (separated). The TwoStep analysis also indicates which of the data (six wheelchair mobility performance outcomes) was of most importance for clustering. The factor for importance to the model prediction can range from 0 (unimportant) to 1 (most important). This information helps to gain insight in the bases for the clustering model, and the contribution of each performance outcome.



A close-up, low-angle photograph of a wheelchair's metal frame. The frame is made of polished, reflective metal tubes that create a complex geometric pattern of lines. In the lower-left foreground, a white, rectangular electronic device is mounted on the frame. It features a prominent orange circular sensor on its top surface and a black strap or band around its middle. The background is a bright, out-of-focus white, which makes the dark metal frame stand out. The overall composition is technical and modern.

# Chapter 7

## Wheelchair properties and performance

Wheelchair Mobility Performance enhancement by changing wheelchair properties; what is the effect of grip, seat height and mass? *International Journal of Sports Physiology & Performance*



## Chapter 7: Wheelchair properties and performance

### Wheelchair Mobility Performance enhancement by changing wheelchair properties; what is the effect of grip, seat height and mass?

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#### Abstract

**Purpose:** The purpose of this study was to provide insight in the effect of wheelchair settings on wheelchair mobility performance.

**Methods:** Twenty elite wheelchair basketball athletes of low (n=10) and high classification (n=10), were tested in a wheelchair basketball directed field test. Athletes performed the test in their own wheelchair, which was modified for five additional conditions regarding seat height (high - low), mass (central - distributed) and grip. The previously developed, inertial sensor-based wheelchair mobility performance monitor (van der Slikke et al., 2016), was used to extract wheelchair kinematics in all conditions.

**Results:** Adding mass showed most effect on wheelchair mobility performance, with a reduced average acceleration across all activities. Once distributed, additional mass also reduced maximal rotational speed and rotational acceleration. Elevating seat height had effect on several performance aspects in sprinting and turning, whereas lowering seat height influenced performance minimally. Increased rim grip did not alter performance. No differences in response were evident between low and high classified athletes.

**Conclusion:** The wheelchair mobility performance monitor showed sensitive to detect performance differences due to the small changes in wheelchair configuration made. Distributed additional mass had the most effect on wheelchair mobility performance, whereas additional grip had the least effect of conditions tested. Performance effects appear similar for both low and high classified athletes. Athletes, coaches and wheelchair experts are provided with insight in the performance effect of key wheelchair settings, and they are offered a proven sensitive method to apply in sports practice, in their search for the best wheelchair-athlete combination.

**Keywords:** *Wheelchair mobility performance, Wheelchair properties, Paralympic sports, Classification, Wheelchair basketball*

## Introduction

In wheelchair sports, athlete and wheelchair form one functional unit determining individual wheelchair mobility performance (Mason et al., 2013). To enhance performance, athletes could focus on physical progress, technical wheelchair improvement or optimization of the interaction between both. That athlete specific interaction is especially important in adapted sports, since the wide range of physical impairments does not enable global optimization rules that apply to all. Getting the best wheelchair setting for each individual player is usually a long and time-consuming iterative process, with incremental improvements over the years with each new custom-made wheelchair. This approach does not fit elite sports demands at all, where competition demands (near) instant improvements.

To date, the wheelchair fitting process for performance optimization is highly dependent on the experience level of athlete and wheelchair expert. At the elite level, wheelchair experts are likely to adopt scientific knowledge of research describing general effects of wheelchair settings on performance (Laferrier et al., 2012; Mason et al., 2010; Mason et al., 2013), but effects are often described in qualitative general trends, rather than in quantitative effects. More detailed insight into the relationship between key settings, such as seat height/position and performance, could support athletes and wheelchair experts in their decision making. Often, there is not a single performance target, but decisions have to be made on the trade-off; for example, between desirable high seating position for shooting and its assumed negative effect on wheelchair mobility performance. The conditions for this trade-off are highly individual, specified by the athlete's classification, skills and field position.

A prerequisite to quantify the relationship between performance and wheelchair settings, is to have accurate and objective measures. To quote a wheelchair basketball coach: "you can't improve it, if you lack information". In preceding research, a method using inertial sensors proved reliable and accurate (van der Slikke et al., 2015) in measuring wheelchair mobility performance and discriminated well between athletes of different classification and competition levels (van der Slikke et al., 2016; van der Slikke, Bregman, Berger, de Witte, & Veeger, 2017). Using this method, the effect of changes in wheelchair configuration on wheelchair mobility performance, could be tested in sport specific conditions.

To determine the effect of wheelchair settings in an ecologically valid way, this should be tested with athletes in their own sports wheelchair under sport specific conditions. However, because their sports wheelchairs are often custom made, dimensions are set and most settings fixed. Therefore, options to temporarily alter wheelchair properties are limited. Nevertheless, with creative approaches minor adjustments to the configuration of the athlete's own sports wheelchair could be made.

There are various wheelchair settings which are known to have an effect on wheelchair mobility performance. Mason et al. (2013) described five main wheelchair settings and their effect on performance aspects: seat height, seat position, wheel camber, wheel size and gear

ratio. Seat height and position are two of the key wheelchair settings, that are known to affect performance in lab-based measurements. Yet, the effect of setting alterations on wheelchair mobility performance in sport specific conditions remained unknown (Mason et al., 2013). Seat height can be altered in sports wheelchairs to some extent, but seat position (forward-backward) is manipulated less easily in an unambiguous manner. Wheel camber, size and gear (ratio of wheel size-rim) are difficult to modify within regular sports wheelchairs, without affecting a range of other wheelchair characteristics. Wheelchair mass is a common argument towards performance and it can quite easily be altered, albeit only in one direction (adding mass). Finally, additional grip is expected to enhance performance (Cooper, 1990; Lutgendorf, Mason, van der Woude, & Goosey-Tolfrey, 2009; Mason, van der Woude, & Goosey-Tolfrey, 2009). It is common practice to use high friction gloves in wheelchair racing and rugby, but not in wheelchair basketball. Although the use of gloves will probably not find its way into basketball, but alternative ways for increased hand-rim friction might (see supplementary material for more detailed description).

To support athletes and wheelchair experts in their search to optimize wheelchair configuration, the goal of this research was to provide *quantitative* insight in the effect of seat height, mass and grip on wheelchair mobility performance for athletes of low and high classification. The wheelchair mobility performance was measured in a standardised wheelchair basketball directed field test, (de Witte et al., 2017) that athletes performed with: lowered and elevated seat height; with additional mass centrally placed; with additional mass distributed over the wheelchair; with gloves for improved rim grip. Since all conditions could have dissimilar effects on differently classified athletes (van der Slikke et al., 2016), groups of low (1 – 1.5) and high (4 – 4.5) class athletes were included.

Given the known effect of increased seat height on the kinematics and kinetics (Mason et al., 2013), it was expected that elevating the seat would decrease most wheelchair mobility performance outcomes, whereas a lowered seat might improve mobility performance. This effect was expected to be more prominent in the low-class athletes, since they have less trunk function to compensate for changes in shoulder-rim distance. Since adding mass will increase the inertia, movements require more force, so it is expected to reduce mobility performance. If centrally placed, mass mainly affects forward acceleration whereas distributed mass also affects maximal rotational speed and rotational acceleration given the increase in rotational inertia. Maximal forward speed is expected to be less influenced in mass conditions, since the effect of additional mass is less in continuous runs of longer duration. Maximal rotational speeds are more affected by rotational acceleration, since rotations are only of short term by nature. The difference between high and low-class athletes is expected to be less prominent in these conditions, although due to the physical capacity, added weight might have slightly more effect on low-class athletes. The increased grip condition is expected to enhance

performance somewhat, especially in the low-class athletes with sometimes affected hand grip functionality.

## Methods

### *Subjects*

The wheelchair mobility performance was measured in a standardised field test (de Witte et al., 2017), for 20 elite level wheelchair basketball athletes. Athletes played at international (n=7) or national level (Dutch competition, n=13), with a group of ten players of class 1 -1.5 and a group of ten players of 4 – 4.5 (see Table 7.1). Both female (n=7) and male (n=13) athletes were included.

**Table 7.1: Subject characteristics and distribution over classification groups**

	Mean	SD	Class	
			1-1.5	4-4.5
Age (y)	29.7	11.5	34.2	25.1
Height (cm)	179.6	9.1	179.4	179.8
Mass (kg)	71.1	11.8	68.9	73.2
Experience (y)	9.0	9.5	7.9	10.2
Gender (F/M)			4 / 6	3 / 7

This study was approved by the Ethics Committee of the Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, the Netherlands (2016-091R1). All participants signed an informed consent after being informed on the aims and procedures of the experiment.

### *Methodology*

Athletes were familiarised with the field test and performed the ~7-minute test six times, starting with the wheelchair in its common “neutral” setting (N). After that first run, a highly-experienced wheelchair expert changed their wheelchair to one of the five test conditions. The order of the conditions was randomly assigned, to eliminate possible effects of learning or fatigue. The five test conditions were: 7.5% lowered seat height (L); 7.5% elevated seat height (H); 7.5% increased total mass centrally placed at the camber bar (MC); 7.5% increased total mass distributed at 30 cm to the front (~45% total added mass) and to the rear (~45% total added mass) of the camber bar with a custom-made clamp (~10% total added mass, MD); and finally, in neutral setting but with rubberised gloves for increased grip (G). The time in-between tests varied between 15-30 minutes, to allow athlete recovery and wheelchair adjustments.

Wheelchairs settings, especially adjusted seat height, were altered while preserving other chair ratios. So, with elevating or lowering the seat, the height of the backrest and footplate was changed equally. Although a percentage (7.5%) of seat height was used for the adjustment magnitude, the actual change in seat height towards the neutral position was measured on top of the athlete’s head. The magnitude of the additional mass was 7.5% of the initial total mass measured on a weight platform prior to the test.

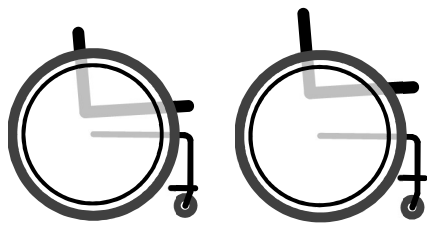


During the field test, each wheelchair was equipped with the “wheelchair mobility performance monitor”, a three-inertial sensor-based method for performance measurement, as described by van der Slikke et al. (van der Slikke et al., 2015; van der Slikke et al., 2016). This method provides six Wheelchair Mobility Performance (WMP) outcomes for each field test measurement. In this method, the measurement is split in sections where the athlete moves. For forward movement a threshold  $>0.1$  m/s was used, and for rotational movement  $>10^\circ/\text{s}$  (van der Slikke et al., 2016). The WMP outcomes are calculated on these sections, they are: average forward speed; average speed in the best two runs (speed sections); average acceleration in the first 2m from standstill; average rotational speed in a curve; average rotational speed in the best two turns (rotation sections); average absolute rotational acceleration. Since the field test consists of 15 separate test items, it is also possible to calculate item specific outcomes. Per test item, two outcomes regarding forward motion and two outcomes regarding rotation were calculated. The outcomes were: maximal forward speed, average forward acceleration, maximal rotational speed and average rotational acceleration. For rotations absolute signals were used, disregarding the direction of rotation.

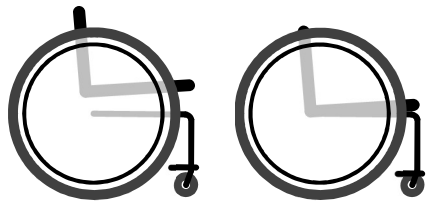
The 15 test items reflect all mobility performance aspects of wheelchair basketball, like a straight sprint (12m), a  $360^\circ$  curve (12m), turning on the spot and combined actions. These items are performed in a regular way, but also with intervals (additional stop/start at 3m/3m/6m in a straight and curved sprint, or with additional stop/start in the turn on the spot at  $90^\circ$ ) and while dribbling a ball (B). The curves and turns were performed in right (R) and left (L) direction. One item covering small back and forward movements was excluded from the analysis, since its execution appeared unreliable in previous research (de Witte et al., 2017).

#### *Comparison of performance outcomes*

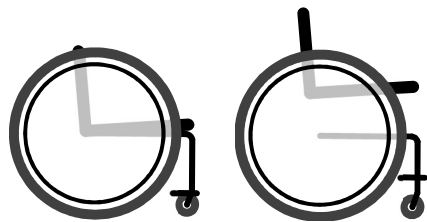
Per field test executed, a total of 62 performance outcomes was calculated: six overall outcomes and four outcomes in 14 test items. These 62 outcomes were compared between the neutral and five test conditions (Figure 7.1). Furthermore, the two tests with lowered and elevated seat were compared, as well as the two conditions with added mass. Since the neutral position does not necessarily resembles the optimal seat height the comparison between both seat height extremes might reveal a more distinct difference. The comparison between both added mass conditions might reveal the specific effect of mass distribution.



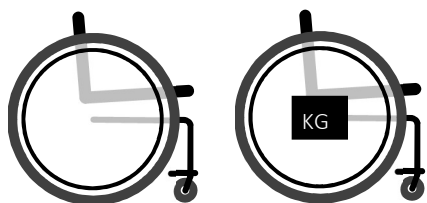
Neutral (N) vs.  
High (H)



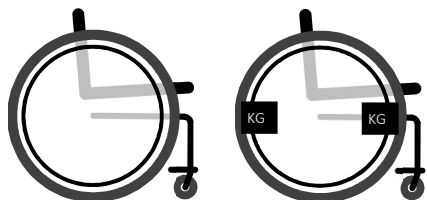
Neutral (N) vs.  
Low (H)



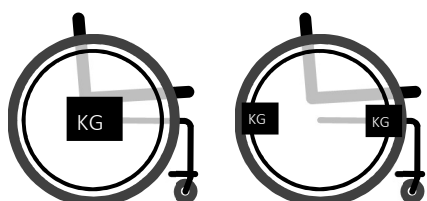
Low (L) vs.  
High (H)



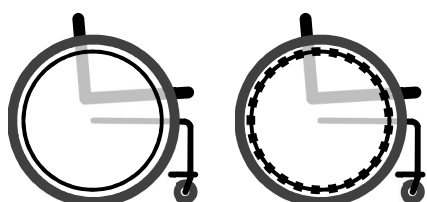
Neutral (N) vs.  
Mass Central (MC)



Neutral (N) vs.  
Mass Distributed (MD)



Mass Central (MC) vs.  
Mass Distributed (MD)



Neutral (N) vs.  
Grip (G)

Figure 7.1: Seven comparisons based on five conditions compared to neutral and two mutual comparisons.

### *Statistical analysis*

To gain insight in the difference magnitude in performance outcomes, Cohen's *d* effect sizes (ES) were calculated based on the *t*-value, the correlation and the sample number (see supplemental material) (Borenstein & Cooper, 2009). The effects were divided in small effect ( $ES = 0.2 < 0.5$ ), moderate effect ( $ES = 0.5 < 0.8$ ) and large effect ( $ES \geq 0.8$ ), as described by Cohen et al. (Cohen, 1988; Cohen, 1992). The possible effect of class on performance difference between conditions is tested for the six WMP outcomes, based on a two-way mixed ANOVA with the class group as between-subject factor. The use of this statistic procedure requires a list of assumptions that must be met. Outliers in the data were checked based on a boxplot and a Kolmogorov Smirnov test was applied for testing normal distribution. Prior to the two-way ANOVA, studentized residuals were calculated and inspected. They were subsequently tested for outliers ( $>\pm 3$ ), tested for normality (Q-Q plot), tested for equality of variances (Levene's test), tested for equality of covariances (Box's test) and sphericity of covariances (Mauchly's test).

## Results

### *Measurements*

All measurements in neutral configuration were performed successfully, but due to technical and practical setbacks, some measurements ( $n=8$ ) of the other conditions were lost or not performed (L,  $n=1$ ; H,  $n=2$ ; MC,  $n=3$ ; MD,  $n=1$ ; G,  $n=1$ ). Given the pairwise analysis, the effect of lost measurements on the results is minimal, but it does affect group size. In three cases, a fixed seat plateau and minimal cushion thickness made the aimed 7.5% lowering of the seat height impossible, so only about 5% was achieved.

### *Performance differences between conditions*

Of the six WMP outcomes in seven comparisons, 12 showed effect sizes over 0.2 in comparisons between conditions. In the detailed outcomes per item in the field test 155 of the 392 (four outcomes  $\times$  seven comparisons  $\times$  fourteen test parts) showed effect sizes over 0.2 (Figure 7.2). All effect sizes and their magnitude are shown in Table 7.2.

## Percentage of Effect Sizes > 0.2

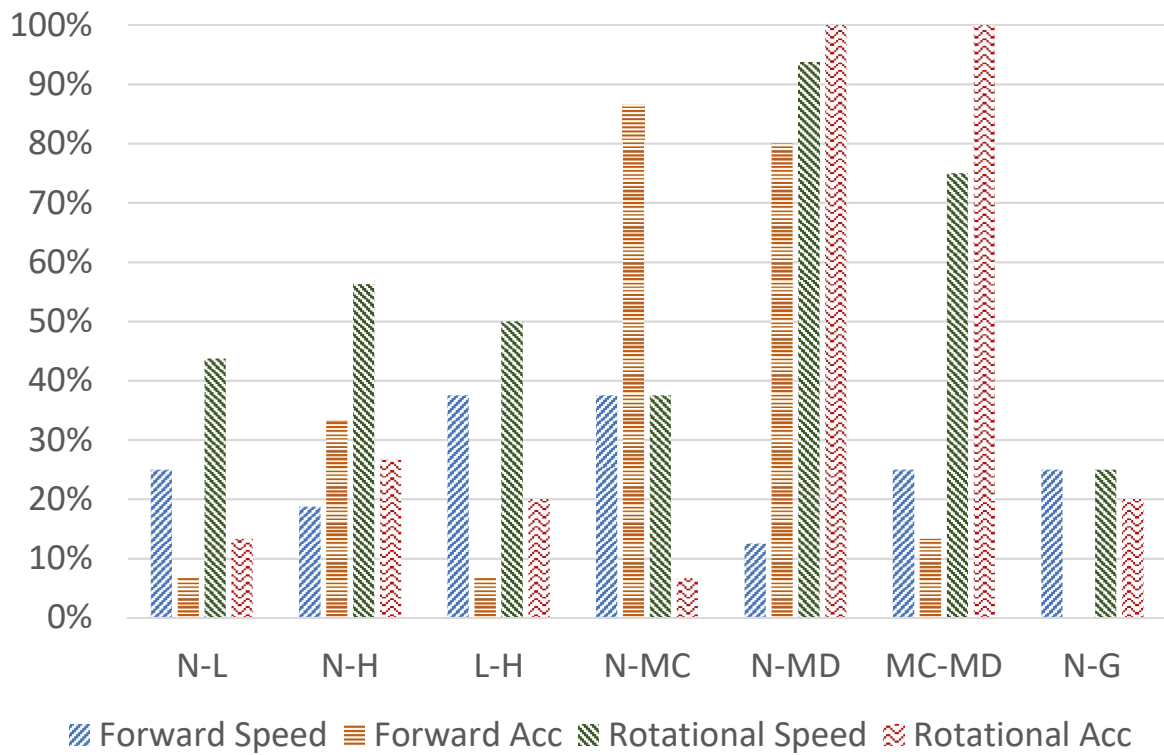


Figure 7.2: this graph shows the percentage of small ( $\geq 0.2$ ) - large effect sizes between conditions, grouped by order (speed / acceleration) and direction (forward / rotational). For forward and rotational speed this is a percentage of 16 (2x WMP-overall + 14 for each test), and for the forward and rotational acceleration this is a percentage of 15 (1x WMP-overall + 14 for each test). Mind that not all outcomes are expected to differ (e.g. forward speed in a turn on the spot), so 100% is not always the upper limit (see Table 7.2 for details).

Table 7.2: Effect sizes (Cohen's d) of significant differences (paired T-test or Wilcoxon Rank,  $p < 0.05$ ), with **small** ( $0.2 < 0.5$ ), **moderate** ( $0.5 < 0.8$ ) and **large** ( $\geq 0.8$ ) marked. The sign indicates performance increase or decrease (-) towards the reference. The table shows the comparison between conditions (indicated left) for the overall test Wheelchair Mobility Outcomes (left column of values) and for four outcomes per field test item. Outcomes are sorted by their direction (forward or rotational), their order (speed or acceleration) and their feature (Avg = average; Best 2 = best 2 actions; 2m = during first 2 meter from standstill; Abs = absolute value; Curve = rotation during driving; Turn = rotation with minimal forward speed). The test items (columns) are grouped by their features, the actual test order differs.

		12m straight					12m curve				Turn on the spot			Comb.					
WMP		Overall	Variable	Regular	Ball	Interval	Right	Left	R ball	L ball	R Interval	L Interval	Right	Left	R interval	L interval	Regular		
Neutral - Low	Forward	Sp Avg	0.17																
		Sp Best 2	-0.09	Abs max	0.21	-0.05	-0.04	-0.10	0.25	0.18	0.08	-0.02	0.14	-0.04	-0.18	-0.20	0.38	0.00	
		Acc 2m Avg	0.02	Abs avg	-0.07	0.13	-0.05	-0.07	0.10	-0.07	-0.13	0.07	0.08	-0.08	0.09	-0.03	-0.29	0.01	
	Rotation	Sp Curve Avg	-0.07																
		Sp Turn best 2	0.02	Abs max	-0.43	-0.57	0.26	-0.46	-0.07	-0.20	0.05	0.10	-0.20	0.18	0.03	0.05	-0.27	0.14	
		Acc Avg	0.05	Abs avg	-0.33	-0.16	-0.13	-0.04	-0.01	-0.19	-0.14	0.10	-0.10	0.24	0.04	0.08	-0.10	0.09	
Neutral - High	Forward	Sp Avg	-0.13																
		Sp Best 2	-0.11	Abs max	0.17	-0.09	-0.26	-0.17	-0.02	-0.09	-0.04	-0.09	0.01	0.34	0.23	0.19	0.09	-0.10	
		Acc 2m Avg	0.07	Abs avg	-0.25	0.26	-0.01	-0.29	0.11	-0.15	-0.14	0.07	0.07	-0.24	-0.16	-0.19	-0.34	-0.10	
	Rotation	Sp Curve Avg	-0.27																
		Sp Turn best 2	-0.30	Abs max	-0.15	-0.36	0.01	-0.22	-0.13	0.11	-0.06	-0.20	-0.17	-0.22	-0.11	-0.20	-0.48	-0.24	
		Acc Avg	-0.13	Abs avg	-0.45	-0.17	-0.13	0.03	0.14	-0.10	-0.12	0.09	-0.15	-0.22	-0.11	-0.34	-0.29	-0.03	
Low - High	Forward	Sp Avg	-0.35																
		Sp Best 2	-0.11	Abs max	-0.17	-0.03	-0.16	-0.06	-0.14	-0.27	-0.05	-0.09	-0.16	0.47	0.35	0.41	-0.27	-0.09	
		Acc 2m Avg	0.00	Abs avg	-0.19	0.11	0.02	-0.25	0.03	-0.02	0.00	-0.04	0.00	-0.11	-0.15	-0.10	-0.13	-0.11	
	Rotation	Sp Curve Avg	-0.25																
		Sp Turn best 2	-0.27	Abs max	0.19	0.00	-0.12	0.20	0.00	0.06	-0.04	-0.28	0.13	-0.38	-0.14	-0.23	-0.26	-0.30	
		Acc Avg	-0.15	Abs avg	-0.05	-0.05	-0.01	0.04	0.20	0.09	0.01	0.02	-0.03	-0.39	-0.18	-0.39	-0.19	-0.12	
Neutral - Weight Central	Forward	Sp Avg	0.03																
		Sp Best 2	-0.01	Abs max	-0.04	-0.21	-0.09	-0.37	-0.22	-0.32	-0.05	0.04	-0.07	0.17	-0.36	0.14	0.30	-0.03	
		Acc 2m Avg	0.02	Abs avg	-0.36	-0.13	-0.30	-0.45	-0.51	-0.42	-0.45	-0.26	-0.23	-0.49	-0.69	-0.37	-0.49	-0.45	
	Rotation	Sp Curve Avg	-0.32																
		Sp Turn best 2	-0.22	Abs max	0.02	-0.63	-0.15	-0.19	-0.11	0.09	-0.16	-0.24	-0.14	0.01	-0.13	0.00	-0.21	-0.39	
		Acc Avg	-0.05	Abs avg	-0.19	-0.14	-0.24	0.04	-0.01	-0.09	-0.06	0.03	-0.03	-0.01	-0.03	-0.10	-0.07	0.02	
Neutral - Weight Distributed	Forward	Sp Avg	0.13																
		Sp Best 2	-0.09	Abs max	0.01	-0.15	-0.05	-0.03	-0.11	-0.18	0.00	0.03	0.06	0.18	0.36	0.02	0.18	-0.20	
		Acc 2m Avg	0.01	Abs avg	-0.32	-0.17	-0.28	-0.52	-0.43	-0.34	-0.41	-0.15	-0.34	-0.39	-0.37	-0.39	-0.59	-0.36	
	Rotation	Sp Curve Avg	-0.21																
		Sp Turn best 2	-0.26	Abs max	-0.54	-1.12	-0.31	-0.63	-0.75	-0.52	-0.45	-0.18	-0.48	-0.27	-0.39	-0.31	-0.41	-0.43	
		Acc Avg	-0.32	Abs avg	-0.40	-0.44	-0.38	-0.53	-0.36	-0.45	-0.43	-0.21	-0.59	-0.29	-0.31	-0.36	-0.35	-0.29	
Weight Central - Weight Distributed	Forward	Sp Avg	0.17																
		Sp Best 2	0.01	Abs max	0.09	0.05	0.05	0.36	0.19	0.18	0.03	0.06	0.14	0.21	0.51	0.02	-0.10	-0.21	
		Acc 2m Avg	0.06	Abs avg	0.14	-0.01	0.04	-0.06	0.07	0.07	0.05	0.16	-0.07	0.18	0.41	-0.01	-0.24	0.07	
	Rotation	Sp Curve Avg	0.02																
		Sp Turn best 2	-0.04	Abs max	-0.69	-0.57	-0.25	-0.49	-0.49	-0.41	-0.24	0.04	-0.34	-0.26	-0.23	-0.35	-0.30	-0.11	
		Acc Avg	-0.29	Abs avg	-0.21	-0.48	-0.23	-0.48	-0.33	-0.42	-0.40	-0.25	-0.58	-0.30	-0.22	-0.27	-0.27	-0.34	
Neutral - Grip	Forward	Sp Avg	-0.10																
		Sp Best 2	-0.16	Abs max	-0.01	-0.12	-0.13	0.30	0.31	0.16	-0.20	0.07	0.18	0.12	-0.09	-0.08	0.32	0.02	
		Acc 2m Avg	-0.08	Abs avg	-0.14	0.13	0.02	-0.04	0.09	-0.07	-0.17	0.07	0.11	0.04	-0.04	-0.01	-0.08	-0.01	
	Rotation	Sp Curve Avg	-0.15																
		Sp Turn best 2	-0.28	Abs max	-0.21	-0.61	0.08	-0.13	-0.04	-0.12	-0.06	0.12	-0.12	0.01	0.05	0.00	-0.27	0.07	
		Acc Avg	-0.07	Abs avg	-0.18	-0.18	-0.14	0.05	-0.06	-0.11	-0.11	0.07	-0.10	-0.04	-0.02	-0.21	-0.20	0.24	

### Classification effect on performance differences between conditions

The possible effect of classification on the main six WMP outcomes between conditions was determined by the two-way mixed ANOVA. For each of the six WMP outcomes, all assumptions linked to this procedure were checked, as shown in Table 7.3. All outliers were checked and ascertained to be genuine. Most of the assumptions were met, however, outliers distorted the distribution especially in the average forward acceleration to 2m in the high-class group. Since data did not seem eligible for transformation correction, procedures were kept and violations noted. With due observance of the few violations, no significant interaction effect of class with any of the six WMP outcomes was found, as shown in Table 7.3.

**Table 7.3: Two-Way mixed ANOVA assumptions tests and interaction outcomes.** The left two columns show the number of outliers (all genuine) and the number of not-normal distributions (out of 12) per class group in the WMP outcomes. The middle 5 columns show: the characteristics of the studentized residuals; with the number of outliers; the number of times data showed non-normality (out of 12); the number of times the Levene’s test showed no equality of variances (out of 12); if there was equality of covariance matrices as determined by the Box’s test; if differences between groups are equal as tested by the Mauchly’s test of sphericity. The right 3 columns show the interaction effect of condition\*class, based on the within subject, with F value, the significance and partial  $\eta^2$ .

			Data		Studentized residuals							
			Outliers	Distribution	Outliers	Q-Q plot	Levene's	Box's test	Mauchly's	F <sub>(5,65)</sub>	Significance	partial $\eta^2$
Forward	Sp	Avg	1	-	-	-	2	no	-	0.90	0.48	0.07
		Best 2	5	1	-	-	4	no	-	0.46	0.80	0.03
	Acc	2m Avg	2	6	-	6	0	no	-	1.52	0.20	0.11
Rotation	Sp	Curve Avg	-	2	-	-	-	-	-	0.97	0.44	0.07
		Turn best 2	9	-	-	-	-	-	-	0.70	0.63	0.05
	Acc	Avg	3	1	-	-	-	no	no	1.33	0.26	0.09

### Discussion

This research showed the effect of altering wheelchair configurations on wheelchair mobility performance and offers athletes and coaches a method to evaluate performance in an objective and ecologically valid way. The WMP monitor combined with the basketball directed field test could be employed as a tool to individually optimize task specific performance of athlete-wheelchair combinations.

The comparison between multiple conditions and several performance outcomes, resulted in a vast amount of values for further analysis. To gain insight in the performance differences between conditions, Cohen’s d effect sizes were used. This measure allows for easy interpretation, but has its limitations given the dependence on the group composition (Dankel et al., 2017). Therefore, raw data and additional statistics are presented in the supplementary material, as are the differences in WMP outcomes expressed in a factor of smallest detectable difference (van der Slikke et al., 2017).

Changes in performance due to the modifications in wheelchair configuration, showed in both positive and negative effect sizes, so they show increase and reduction in outcome values respectively. Which type of change is considered performance enhancement is depending on the outcome, the task executed and the aim of the athlete. Increased rotational speed in “turning” (positive ES) could generally be considered as better performance, whereas increased rotational speed in “a straight sprint” could be regarded as performance reduction, since it implies a less straight track driven. Since wheelchair mobility performance goals might differ between athletes, depending on their field position, classification or other aspects, there is no unambiguous interpretation whether a certain change is regarded as improvement or not. Therefore, the direction of performance changes due to altered wheelchair settings (Table 7.2) are displayed without value judgement.

Compared to the neutral position, the *lowered seat height (L)* showed small to moderate output increases and decreases, mainly in rotational aspects. Reduced rotational speed and acceleration (negative ES) in the straight sprints could be considered as better performance, since it means better maintaining a straight line. As expected, *seat elevation (H)* mainly decreased outcomes, as shown by small negative effect sizes of forward and rotational aspects in sprints (better performance) and turns (reduced performance). In the WMP outcomes both rotational speeds showed a small decrease. In the comparison between low (L) and high (H) seat height, differences per item are less prominent, but now also the WMP average forward speed outcome shows a small decrease for the elevated seat condition. These results are in line with the findings of Mason et al. (Mason et al., 2013) in their review article.

In the condition with *centrally added mass (MC)*, effect sizes of rotational speed WMP outcomes were small. At test item level, forward average absolute acceleration is reduced in nearly all items, with small to moderate effect sizes. Once the same amount of *added mass is distributed (MD)*, the effect on performance is even more profound. The rotational acceleration WMP outcome shows an effect size of -0.32, and at test item level, nearly all rotation related outcomes show small to large effect sizes. Again, reduction of rotational components in straight sprints, could be considered as better performance. So, added mass has effect on acceleration, and once distributed also on rotational acceleration. Due to the short nature of rotations this is also reflected in the maximal rotational speed. In the comparison between centrally placed and distributed added mass, only the rotational components differ.

The condition with improved *grip (G)* due to the use of rubber coated gloves, showed the least effect of all conditions. Of the overall WMP outcomes, best rotational speed in turning shows a small negative effect size. If separated per test item, only a few outcomes show small effect sizes in difference and in most cases with reduced magnitudes of outcomes. Verbal feedback from participants on the use of gloves varied widely, so maybe this condition is beneficial for some, but unprofitable for others. Furthermore, this condition seemed to have more impact

on propulsion technique than any of the other conditions, possibly requiring additional learning time to optimize grip benefits.

Differences between conditions show more explicit in the analysis per test item, compared to the overall WMP outcomes. This implies that although the six WMP outcomes have been proven to discriminate well between athletes (van der Slikke et al., 2016), they might lack enough specificity for individual athlete-wheelchair optimisation. If the aim is to optimize an athlete-wheelchair combination for a specific task, like straight sprinting, analysis based on a task directed field test provides more specific information. By combined tasks that occur in match play, the performance increase by reduced rotational speed in straight sprinting and increased rotational speed in turning, might cancel out.

Since the WMP monitor method also allows for more detailed analysis, additional performance differences were identified at test item level. The four outcomes used were selected since they are rather easy to interpret, with the maximal (rotational) speed, and the average (rotational) acceleration reflecting movement intensity. Maximal forward speed seems to be least affected by the different conditions, whereas the other three do discriminate depending on the condition. In future analysis, the current measurement configuration can be used to detect tasks (turning, sprinting, curve, etc.), allowing for task specific display of kinematic outcomes. The WMP monitor enables research into the relationship between these outcomes and overall game performance, which could be highly beneficial for coaches and athletes.

This research showed the magnitude of effect on performance due to changes in wheelchair configuration, but it does not yet quantify the relationship between configuration and performance as expressed in a regression equation. For most settings, the possible relationship between setting and performance is expected to be non-linear, with reduced performance near the setting boundaries. This assumption implies that for each setting multiple conditions (>3) are required to fit any regression equations. In this study, only seat height was measured in three conditions (low-neutral-high) and all others only in two conditions. Furthermore, given the heterogeneity of the group of wheelchair athletes, it is uncertain if a valid regression equation could be established, even if performance is measured in more conditions. Possibly if large volume performance data is available, it is possible to divide (by classification or impairment) the athletes in more homogenic sub-groups, to allow for regression analysis of the settings that appeared of importance.

Given the scope of this study, methodological choices had to be made that raised some limitations. All tests were performed consecutively, with limited time for the athlete to get acquainted to each new condition. Enough time in-between tests was allowed for full physical recovery, but not for full physical or coordinative adaptation. Since only minor modifications (~7.5% mass and height) were made, athletes experienced no difficulty with performing the field test with adjusted wheelchair settings. Only in the “grip” (G) condition, some athletes remained unaccustomed to the gloves throughout the test.



Although it was anticipated that classification level could cause different performance effects as a result of changes in wheelchair settings, no interaction effect of classification was uncovered. This finding needs to be adopted with care, since the number of athletes included in this study was limited and there was a clear age difference between groups. Furthermore, some violations to the numerous assumptions linked to the two-way mixed ANOVA procedure occurred.

### Practical Applications

The WMP monitor used, proved responsive to changes in wheelchair mobility performance due to altering wheelchair configuration. As such, it is considered a valuable tool for optimizing individual wheelchairs, reducing time and costs to get to the best athlete specific custom-made wheelchair. In this optimization process, research outcomes can guide the way in decision making regarding the different performance trade-offs. Although relationships between settings and performance have not yet been described by possible regression equations, some first quantitative insight of effect is provided. Given the range of outcomes and quantities, differences are only described in effect sizes. Evidently, in sports practice, actual outcomes could be used. For example, the difference in maximal speed in the 12m sprint between neutral (3.98 m/s) and lowered seat height (4.07 m/s) is expressed as an effect size of -0.21, which resembles a speed difference of - 0.09 m/s.

Within the measured range, lowering seat height has minimal effect, whereas elevating seat height reduces performance. Added mass reduces forward acceleration and if mass is distributed in forward-backward direction, it has considerable effect on rotation performance. Distributed mass also reduces rotation in a straight sprint, which could be considered positive in some game aspects, but it reduces manoeuvrability in most other aspects. This outcome could endorse athletes to try and reduce mass to the front and rear, in particular try to move the foot plate as far back as possible and configure wheel and seat position in such a way that the mass is most centrally placed and close to the camber bar. That solution is only applied occasionally, but seems quite beneficial regarding mobility performance. Furthermore, it is advised to align the wheelchair in such a way that the fore-backward location of the overall centre of mass is close to the rear axle, in the most frequently used body position (not necessarily upright position!).

### Conclusion

It proved feasible to execute research regarding wheelchair settings with elite level athletes in their own custom made sports wheelchairs. The standard six wheelchair mobility performance outcomes do differ between some conditions, but with opposite demands across tasks, performance effects are sometimes levelled out in the used outcomes. The more detailed analysis per field test task showed of additional value, by enhancing specificity.

Seat height affected outcomes of both forward and rotational movement. Centrally added mass affected mainly forward motion outcomes, and once distributed it also affected

rotational outcomes. Within the limitations of this study, the classification of an athlete does not seem to cause different effects on wheelchair mobility performance.

The WMP monitor showed to respond to minor changes in wheelchair configuration, so in future athletes, coaches and wheelchair experts can apply this cheap and easy accessible method for continuous mobility performance monitoring to evaluate optimisation interventions in training and wheelchair setting.

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#### Conflict of interest statement

None.

A close-up, low-angle shot of a wheelchair's metal frame, showing the intricate network of silver-colored tubes. A white, rectangular electronic device with a prominent orange circular button is mounted on the frame. The background is a bright, out-of-focus white, suggesting an indoor sports arena.

# Chapter 8

## Performance in wheeled sports compared

To team up or to battle; how do wheelchair court sports compare regarding wheelchair mobility performance?



## Chapter 8: Performance in wheeled sports compared

To team up or to battle; how do wheelchair court sports compare regarding wheelchair mobility performance?

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### Abstract

Only limited information on wheelchair mobility performance (WMP) across court sports is available. Better insight in WMP resemblances and differences between sports could aid athletes and wheelchair experts in their performance optimisation quest, by pinpointing which characteristics are sport specific and which are applicable court sport wide.

WMP was measured in match play for 29 basketball athletes, 32 rugby athletes and 15 tennis athletes. As hypothesized based on sport characteristics, wheelchair basketball athletes show the best WMP outcomes and wheelchair rugby the lowest, whereas wheelchair tennis athletes range in-between. The well quantified WMP profiles, could be used to support in individual performance perfection, but also for optimizing wheelchair design and sport referral in the rehabilitation process.

**Keywords:** *Wheelchair mobility performance - Wheelchair characteristics - Wheelchair basketball – Wheelchair tennis – Wheelchair rugby - Paralympic.*

## Introduction

Wheelchair basketball, tennis and rugby range within the most spectacular Paralympic sports, with increasing popularity and international competitions being held worldwide. With the rising level of professionalism, coaches, athletes and wheelchair experts seek evidence-based support to set-up appropriate training schedules, match preparation routines and optimal wheelchair configuration. In wheelchair sports, it is the interaction between athlete and chair that enables wheelchair propulsion and the movements across the court as required within a given sport (Goosey-Tolfrey, 2010). So, in optimizing performance in wheeled sports, three components and their interactions need to be taken into account: the *athlete*, the *wheelchair* and the *sport*. To enhance performance, some information regarding the physiology can be obtained from able bodied sports, but due to impairments in wheelchair sport athletes, not all general principles apply. Compared to able bodied sports performance perfection, wheelchair athletes face more challenges, since there are more individual characteristics that need to be taken into account (e.g. impairment), there is less scientific based expertise available and the optimization always needs to take the three main factors into account: *athlete*, *wheelchair* and *sport*.

In all wheelchair court sports, the overall game performance is highly dependent on individual wheelchair mobility performance (van der Slikke et al., 2016), so a method that provides insight in this aspect could support wheelchair athletes in solving the performance optimization challenges. Furthermore, the wheelchair mobility performance closely relates to the *athlete-wheelchair* interaction, covering two of the main components in wheeled sports (Mason et al., 2013). To address the third component (sport), wheelchair mobility performance should be measured across sports, to obtain insight in the resemblances and differences per sport. General differences in mobility performance between sports could well be hypothesised, but quantification is needed to be of use in performance optimisation. The quantified resemblances could be enforced to team up between wheelchair sports in developing training guidelines or perfecting wheelchair configuration, whereas the differences could guide in differentiated sport specific approaches. This research describes the similarities and discrepancies between wheelchair tennis (WT); basketball (WB); and rugby (WR) and its expected effect on wheelchair mobility performance. The Wheelchair Mobility Performance Monitor was used to quantify the differences in mobility performance during match play.

### *Wheelchair courts sports compared*

#### **Court dimensions and ratio**

One of the most evident factors with an effect on wheelchair mobility performance are the court dimensions. Within wheelchair basketball, Mason et al. described the effect of the court ratio per player on outcomes of mobility performance (Mason, van der Slikke, Hutchinson, Berger, & Goosey-Tolfrey, 2017). A reduced court ratio per player would typically result in lower distances travelled and lower average speeds. Wheelchair basketball and rugby are

played on the same court dimensions (28x15m), with basketball played with two teams of five players (~42m<sup>2</sup> per player) and rugby with teams of four players (~53m<sup>2</sup> per player). The court area of a single wheelchair tennis player is 11.89 x 8.23m (~98m<sup>2</sup> per player), but of course the actual area used could be extended behind the baseline and to the sides. Although court ratio per player will have an effect on average speed, maximal speed is more likely to be constrained by absolute field dimensions. Furthermore, reduced court space might have an inversed effect on rotational speeds, since more manoeuvrability is required.

### **Ball and racket handling**

Another factor that separates wheelchair tennis apart from rugby and basketball is the constant presence of the racket, that affects mobility performance. The use of a racket reduces the maximal speed by 0.18 m/s, whereas the acquired speed in the first three pushes is significantly reduced (Goosey-Tolfrey & Moss, 2005). Although not described in literature, the reduced hand-rim grip due to holding the racket, is most likely to affect manoeuvrability in a similar way, especially in a turn on the spot. Of course, the wheelchair mobility performance of rugby and basketball players will also be affected during ball handling, but those occasions are of short nature.

### **Wheelchair weight and dimensions**

Regarding wheelchair design, an important factor is whether or not wheelchairs could collide. In wheelchair tennis the opponent is on the other side of the net, so wheelchairs can be fitted with lightweight carbon rims for example, which would not hold in basketball or rugby. Wheelchair rugby ranges on the other end of the spectrum, where contact is intended and frequent high impact collisions occur, resulting in heavier and bulkier wheelchair designs. The added weight and sometimes longer wheelbase (for stability), have a negative effect on wheelchair mobility performance (van der Slikke, Bregman, Berger, & Veeger, 2018).

### **Impairment and classification**

Since the three sports have different impairment eligibility rules, that aspect might also affect average wheelchair mobility performance. For wheelchair tennis all athletes are eligible, but as a consequence only athletes with the least impairment towards upper extremity survive in competition (quad-tennis aside). In wheelchair rugby, only athletes with irreversible impairment of all limbs are eligible, so with the highest impairment level in wheelchair sports. The wheelchair basketball athletes range in-between both other sports. The level of impairment has significant effect on wheelchair mobility performance (van der Slikke et al., 2017; Vanlandewijck, Verellen, & Tweedy, 2011), so differences in “average impairment level” per sport would also have their effect on wheelchair mobility performance.

## Physiology and intensity

Regarding the physiological demands, Croft et al concluded that wheelchair basketball requires high intensity training loads, whereas tennis requires “training across the exercise intensity spectrum”. (Croft, Dybrus, Lenton, & Goosey-Tolfrey, 2010). A similar pattern was found earlier by Coutts (Coutts, 1988), showing an average heartrate of 127 bpm for wheelchair tennis and 149 bpm for basketball. Barfield et al. reports a slightly lower intensity (118 bpm) in wheelchair rugby, albeit for sport specific training (Barfield, Malone, Arbo, & Jung, 2010). Abel et al. measured energy expenditure during typical sport specific training and found a similar order between sports:  $374.8 \pm 127.1$  kcal/h for wheelchair basketball,  $325.8 \pm 73.0$  kcal/h for wheelchair tennis and  $248.5 \pm 69.4$  kcal/h for wheelchair rugby (Abel, Platen, Vega, Schneider, & Strüder, 2008). So, regarding the intensity and the physiological aspects, information on the comparison between wheelchair sports is available for match play and training. These differences could be explained to some extent by the sport specific characteristics, like court dimensions, individual or team play, ball or racket handling, eligibility of athletes, and so on, but those relationships are quite indirect. Measuring the wheelchair mobility performance could fill that gap, since it provides information on how sports characteristics determine wheelchair kinematics, and wheelchair kinematics in turn could provide information on sport intensity.

### *Aim of this study*

The aim of this study was to quantify the expected resemblances and differences in wheelchair mobility performance between court sports, using the wheelchair mobility performance monitor. Earlier studies showed the sensitivity of this method towards performance differences due to competition and impairment level (van der Slikke et al., 2016; van der Slikke et al., 2017) in wheelchair basketball and modifications in wheelchair configuration (van der Slikke et al., 2018), but it was not yet shown to what extent it pinpoints expected performance differences between sports. It is hypothesized that in a comparison, wheelchair rugby athletes will (on average) show the lowest wheelchair mobility performance on all aspects, since the impairment level is the highest and the wheelchairs are designed for robustness over agility. Wheelchair basketball is played on the same court size, but with (on average) less impaired players and wheelchairs that are more configured for manoeuvrability, so it is expected that these athletes show the highest wheelchair mobility performance in match play. Finally, wheelchair tennis athletes are the least upper extremity impaired athletes, but the nature of the sport poses quite different performance requirements. Court dimensions restrict maximal forward speeds, and the absence of an opponent within the own court side reduces the need for abrupt changes of direction or speed. Therefore, the wheelchair mobility performance of tennis players is expected to range between rugby and basketball, except for the rotational speeds that are expected to range highest or at least similar to wheelchair basketball.



## Methods

### Subjects

Wheelchair mobility performance was measured in a match (van der Slikke et al., 2016) for a group of elite wheelchair basketball athletes (n=29), a group of elite wheelchair rugby players (n=32) and a group of elite wheelchair tennis players (n=15, no quads, Table 8.1). The wheelchair basketball athletes were measured during eleven premier division competition matches and friendly international level matches (GBR, NLD, ISR & AUS). The wheelchair rugby players were measured during the Dutch national championship of 2016, during a practice match of the Dutch national team and at the Amsterdam Quad Rugby Tournament 2017 (NLD, CHE, DEU, FRA, BEL, CZE). Finally, wheelchair tennis players were measured during the 2016 Dutch championship and the ABN-AMRO wheelchair tennis tournament of 2017 (NLD, ARG, FRA, GBR, RSA, ESP).

**Table 8.1: Participant characteristics.** For the class, additional grouping was applied with a low-class group consisting of class 1 – 2.5 for wheelchair basketball and 0.5 – 2 for wheelchair rugby. The high-class group consisted of 3+ for wheelchair basketball, 2.5+ for wheelchair rugby and all athletes for wheelchair tennis.

	Total	Class										N.A.	Class Low/High	Sex M/F	Level Int./Nat.	
		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5					
Basketball	29		5	4	3	5	3		4	5			17/12	20/9	12/17	
Rugby	32	5	4	3	8	4	5	3					20/12	29/3	13/19	
Tennis	15												15	0/15	4/11	5/10

For wheelchair basketball and rugby, this study was approved by the ethical committee of the department of Human Movement Sciences, Vrije Universiteit Amsterdam, and for wheelchair tennis measurements by the Human Research Ethics Committee (HREC) of the TU Delft. All participants signed an informed consent after being informed on the aims and procedures of the experiment.

### Methodology

Each athlete's own sports wheelchair was equipped with three inertial sensors (x-IMU for wheelchair basketball, X-IO technologies; Shimmer3 for wheelchair tennis and rugby, Shimmer Sensing), one on each rear wheel axis and one on the rear frame bar, as described by van der Slikke et al. (van der Slikke et al., 2015; van der Slikke et al., 2015a). This measurement setup with three inertial sensors is also known as the Wheelchair Mobility Performance Monitor (van der Slikke et al., 2016), and provides a standardised plot with six key kinematic performance outcomes. For the analysis, each measurement is divided into sections of speed  $>0.1$  m/s and rotational speed  $>10^\circ/s$ , on which the following outcomes are calculated: average speed; average best speed (of best 5 runs/speed sections); average acceleration in the first 2m from standstill; average rotational speed during a curve (forward speed above average); average best rotational speed during a turn on the spot (of best 5 turns/rotational speed sections, with forward speed below average speed) and average rotational acceleration. In this method, the

cut off speed between “turn” and “curve” is the average forward speed, previously determined as 1.5 m/s in wheelchair basketball. In the other sports analysed in this study, different average speeds might occur, therefore a cut-off at the rounded (at 1 decimal) average speed per sport will be used.

Next to the standard WMPM outcomes, also the distribution of time spent in certain speed zones is calculated, as described for wheelchair rugby (Rhodes et al., 2015), wheelchair tennis (Sindall et al., 2013), and wheelchair basketball (Mason et al., 2017). Based on the used thresholds, a division was made in 0 - 0.5 m/s; 0.5 – 1.5 m/s; 1.5 – 2.5 m/s and over 2.5 m/s, and additionally negative speeds were included as a separate speed zone. The WMPM also measures rotational speeds, so time spent in rotational speed zones could also be calculated. (van der Slikke, Mason, Berger, & Goosey-Tolfrey, 2017) Absolute (disregarding rotational direction) rotational speeds were classified in: 0 – 25 °/s; 25 – 50 °/s; 50 – 100 °/s; and 100+ °/s.

Impairment level as expressed in the classification is known to have an effect on all mobility performance outcomes (van der Slikke et al., 2016), so the differences in impairment level of athletes competing per sport will also typify the results. To estimate to what extent average impairment level influenced performance outcomes, a separate analysis was made for the least impaired athletes per sport only. This “high-class” group consisted of class 2.5+ athletes for wheelchair rugby, of class 3+ athletes for wheelchair basketball, and of all athletes for tennis. These athletes are at least *more* compatible, since athlete population per sport does not allow for complete impairment matching across sports.

For all outcomes, means, standard deviations and differences between sports were calculated, both for the entire group as well as for the “high-class” selection. The significance of the difference was determined using a one-way ANOVA with Bonferroni post-hoc test ( $p < 0.05$ ), preceded by a Kolmogorov-Smirnov test for normal distribution.

## Results

Average speed was highest in wheelchair basketball ( $1.57 \pm 0.13$  m/s), followed by wheelchair tennis ( $1.34 \pm 0.13$  m/s) and wheelchair rugby ( $1.13 \pm 0.27$  m/s). A similar order was visible in the maximal speeds achieved (WB =  $4.98 \pm 0.43$  m/s; WT =  $4.40 \pm 0.40$  m/s and WR =  $3.37 \pm 0.99$  m/s) and in the maximal rotational speeds (WB =  $388 \pm 71$  °/s; WT =  $369 \pm 79$  °/s and WR =  $303 \pm 43$  °/s). Mind that these maximal (rotational) speeds are the average of the best five speeds measured, whereas the average of the “best (rotational) speed” in the WMP-outcomes represents the average of the five best *sections* from start to stop ( $>0.1$  m/s for speed and  $>10$  °/s for rotational speed). For the cut-off between “turn” and “curve” in the WMP outcomes, the average speed was used, with a speed of 1.5 m/s for WB (as used in the original method), a speed of 1.3 m/s for WT and a speed of 1.1 m/s for WR.

For the WMP outcomes (Figure 8.1), the order of sports is the same, with highest performance values in WB, closely followed by WT and WR last. Only in rotational speeds WT athletes slightly outperform WB athletes. Within the selection of “high-class” players the differences between WR and WT decrease (Figure 8.2). All mean values, standard deviations and an overview of significant differences between sports are included in the supplementary material.

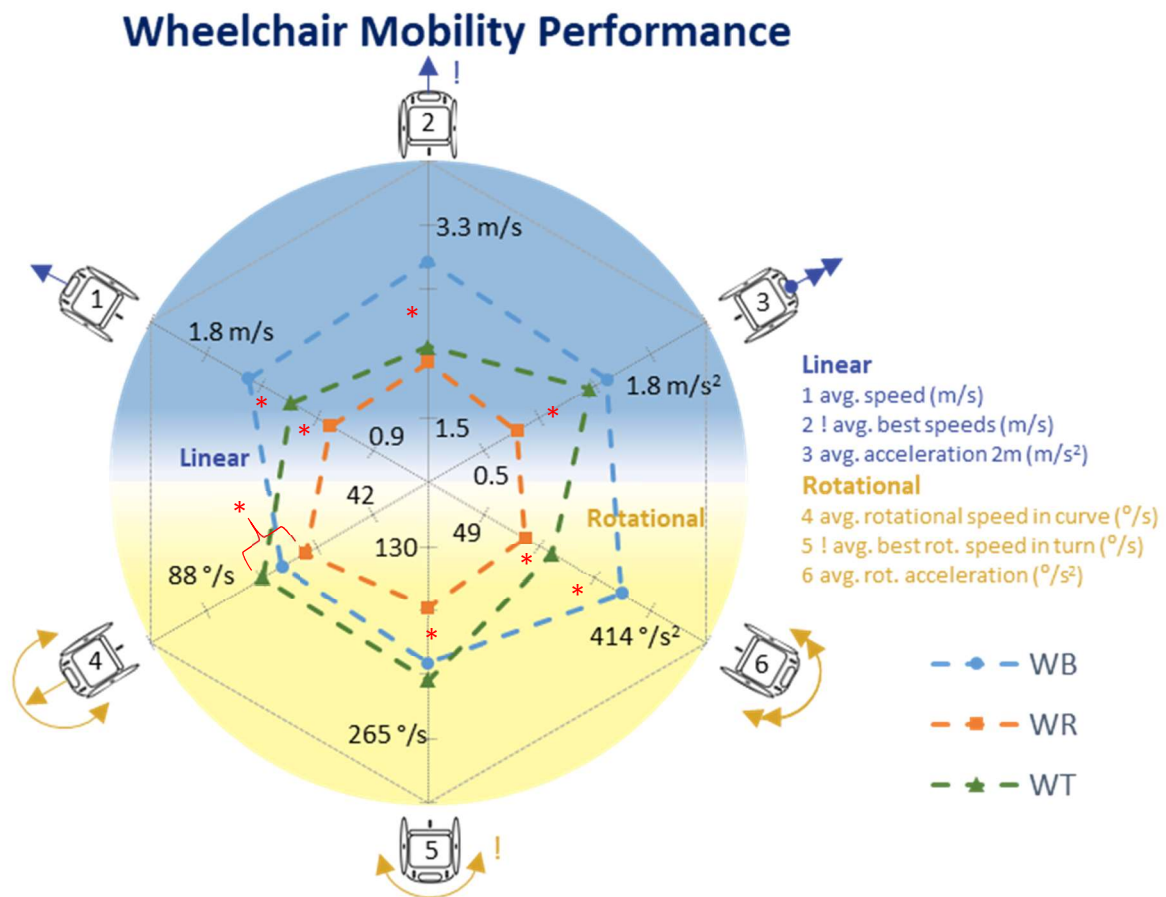


Figure 8.1: WMP for all sports. Significant ( $p < 0.05$ ) differences are marked with a \*. For the tables with values, please see supplementary material.

## Wheelchair Mobility Performance

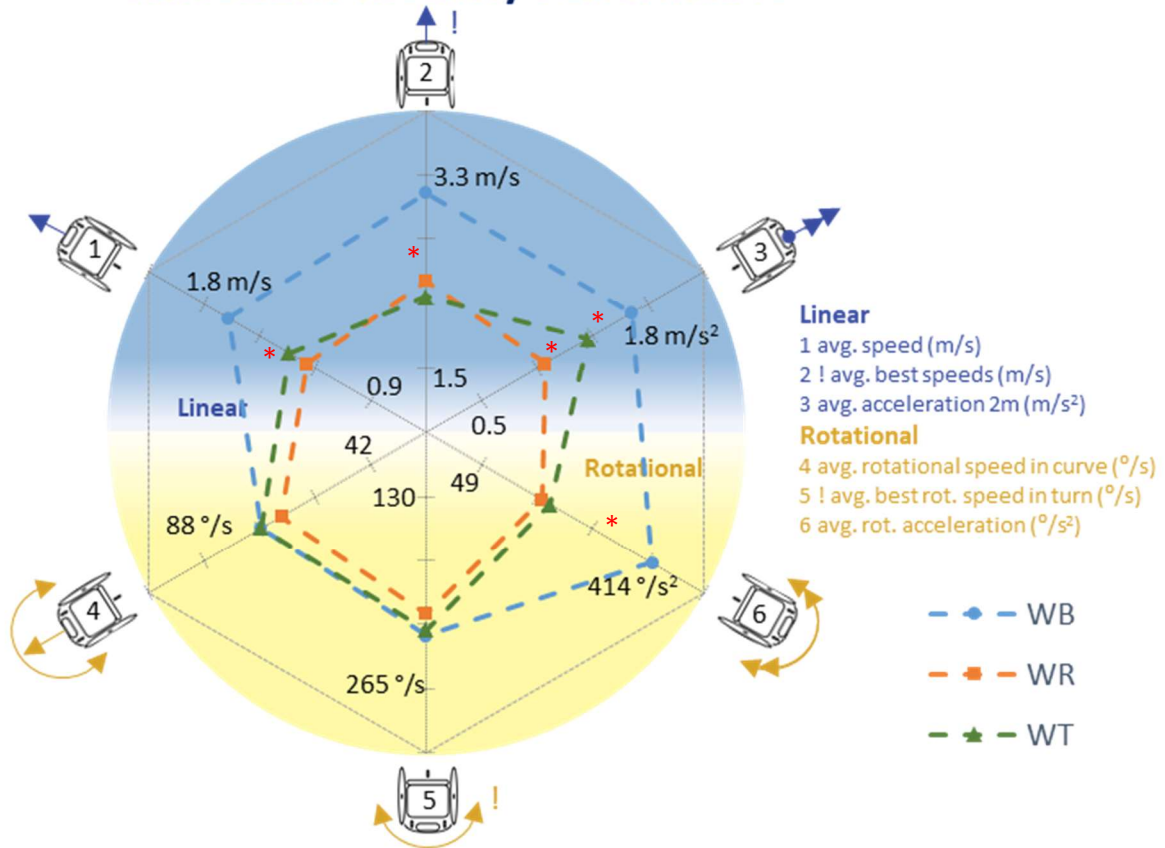


Figure 8.2: WMP for all sports for “high-class” athletes only. Significant ( $p < 0.05$ ) differences are marked with a \*. For the tables with values, please see supplementary material.

In all sports, a substantial amount of time  $\pm 10\%$  was spent in reversed speed (Figure 8.3). Most of the time was spent in the zone that incorporated the average speeds of tennis and rugby (0.5 – 1.5 m/s). In wheelchair tennis, the most time above average speed was spent in the 1.5 – 2.5 m/s zone, with only minimal time in the 2.5+ m/s zone. For wheelchair basketball, also considerable time was spent in the 2.5+ m/s speed zone.

In rotational speeds, differences between distribution in zones were less prominent, albeit that still quite some differences between sports were statistically significant (Figure 8.4). The one clear deviation was the additional time of wheelchair rugby players in the lowest zone and the reduced time in the 100+°/s zone.

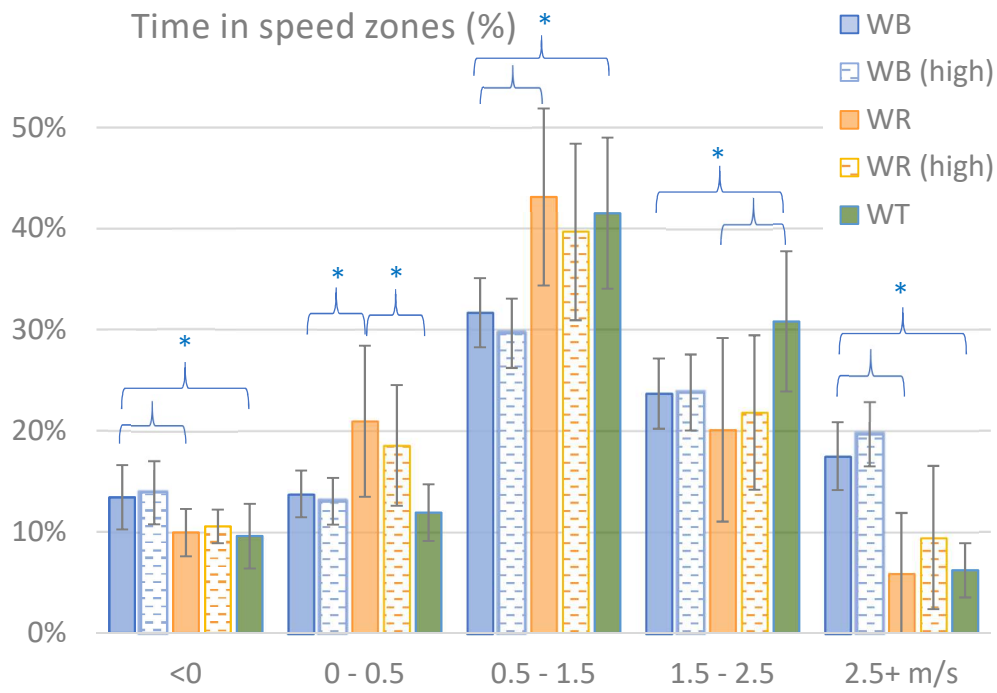


Figure 8.3: distribution of time spent in speed zones, with significant ( $p<0.05$ ) differences marked with \*.

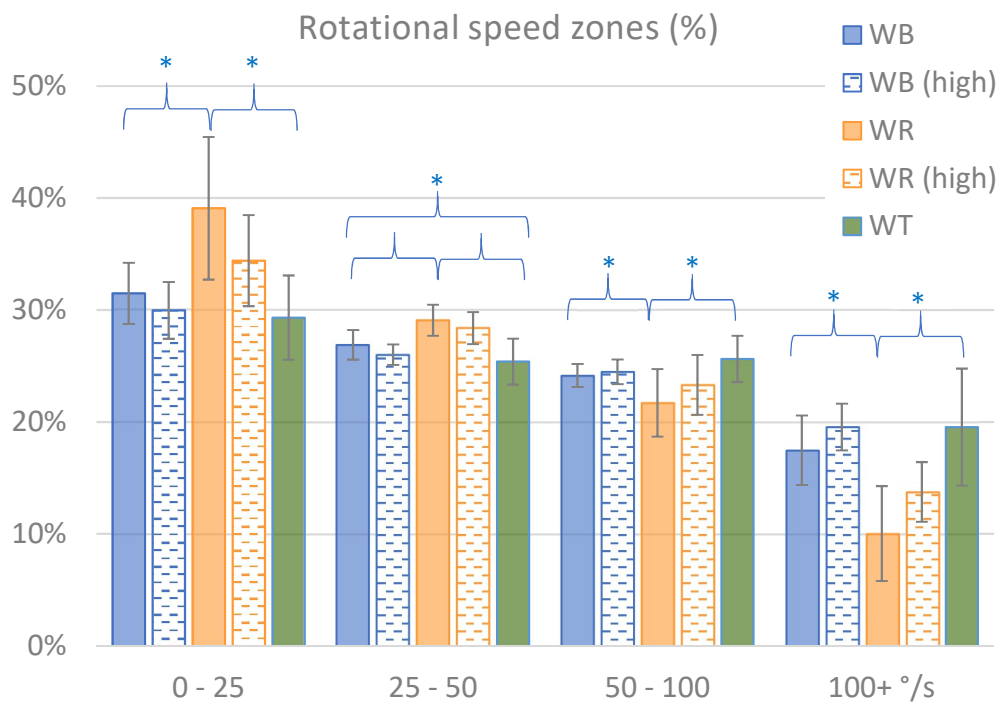


Figure 8.4: distribution of time spent in rotational speed zones, with significant ( $p<0.05$ ) differences marked (\*).

## Discussion

The aim of this study was to quantify wheelchair mobility performance profiles across court sports and to relate differences found to the expectations based on sports characteristics. Wheelchair basketball showed the highest wheelchair mobility performance outcomes, and the most time spent in high (rotational) speed zones. Wheelchair tennis mobility performance followed, with rotational speeds and time spent in high rotational speed zones quite similar to basketball, as expected. Wheelchair rugby players show the lowest mobility performance on average, as anticipated based on the heavier wheelchairs and highest level of impairment of the athletes.

As expected, regarding wheelchair mobility performance, wheelchair rugby appears to be the least intense game of the three. Five out of six WMP outcomes were significantly lower compared to both wheelchair basketball and wheelchair tennis. Once only the least impaired athletes were selected, the differences with wheelchair tennis diminished. Only the average acceleration in the start of a sprint still showed a significant difference. The differences with wheelchair basketball maintained, so it is likely that the initial differences found were mainly a consequence of the lower classified athletes in wheelchair rugby. This finding is in line with van der Slikke et al. (2016), who concluded that there was a steep performance drop of athletes with low classification (class<2) compared to the remaining athletes (class 2+).

The differences between wheelchair rugby and wheelchair basketball are clear for all performance aspects, even if only “high-class” athletes are included. These differences could be explained by the average impairment level and the nature of the game demanding a more stable and heavy wheelchair design.

Even with the -on average- more impaired athletes in wheelchair basketball compared to wheelchair tennis, four out of six performance outcomes show higher values, only rotational speeds range similar. The absence of a nearby opponent reduces the need for abrupt manoeuvres, so motions will be more fluently and less intense (less forward or rotational accelerations). As hypothesised, the field size difference could explain why forward speeds are lower compared to basketball, whereas rotational speeds are not.

The wheelchair mobility performance profiles represent match play, so with all sport specific influences taken into account. A more isolated field test could be used to determine the athlete’s *maximal* wheelchair mobility performance as described by van der Slikke et al. (2017) In such a test, wheelchair tennis athletes will likely range highest, since they are on average least impaired. Those additional measurements could discriminate if differences in mobility performance level could be attributed to the sport or to individual athlete performance level.

For the quantification of the differences presented, it should be kept in mind that this study has some limitations. It is difficult to perfectly match athletes of the different sports measured, for level, match time, and so on. The athletes included were to some extent matched for

competition level and sex, but different athlete selections could have provided slightly different results. This study is meant as a first draft for this type of research, whereas large scale measurements in all three sports are foreseen in future projects. Once more performance data of athletes in competition are present, selections for comparison could be better matched for competition level, impairment (classification) and sex. Another aspect that needs to be regarded, is that the WMPM was initially developed for wheelchair basketball (van der Slikke et al., 2016), with a selection of key wheelchair kinematic outcomes based on basketball match play. To assure that the same kinematics typify the other sports as well, a similar procedure to extract key outcomes should be executed. For this research already, a minor adjustment was made by using a sport specific speed threshold for differentiating between curve and turn (1.1 m/s for WR, 1.3 m/s for WT and 1.5 m/s for WB).

Since the wheelchair mobility performance monitor well quantified differences between sports, it could be employed as a tool for various applications. Cooper et al. described the communalities and differences between wheelchairs for the different sports, and stretches the need for optimal wheelchair configuration, not only to attain best performance but also to reduce the risk of injuries (Cooper & De Luigi, 2014). Therefore, an image of each *sport* is needed regarding the intensity and structure per match play, to adjust wheelchair design and configuration. Furthermore, monitoring the performance throughout the season could indicate training status and identify potential risks of overuse injuries.

#### Practical application

The inertial sensor-based wheelchair mobility performance monitor appeared applicable across wheelchair court sports, both from a practical perspective as for its added value. It could be used to study across sports (referral, wheelchair design, training requirements), within sports (classification, wheelchair design, team composition) and within individual athletes (training load, fatigue, wheelchair configuration). The main outcomes of the method as presented in the WMP-plot could be used as primary outcome, but the method itself also allows for more tailormade representation of wheelchair kinematics, with more emphasis on the physiological aspect (e.g. fatigue, training effect). Figure 8.5a shows a typical example of the WMP-plot of a 3-set wheelchair tennis match of one of the best wheelchair tennis players. Next to the overall summary plot, it is also possible to display the course of the match for a specific performance outcome (Figure 8.5b).

## Wheelchair Mobility Performance

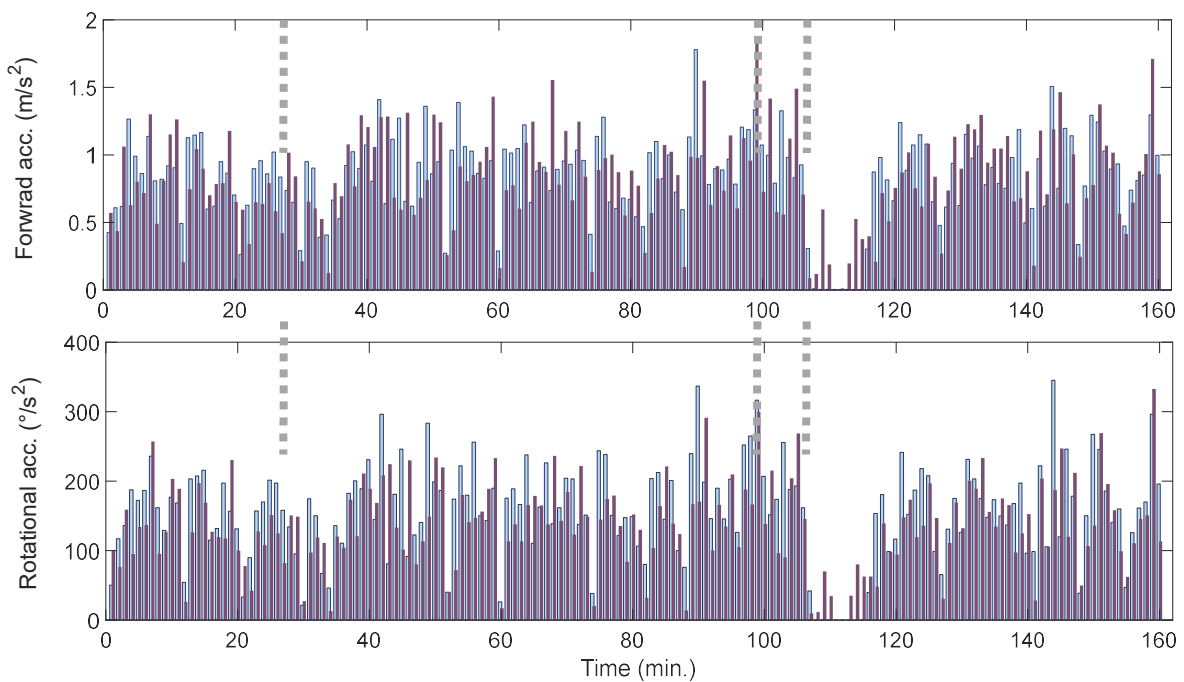
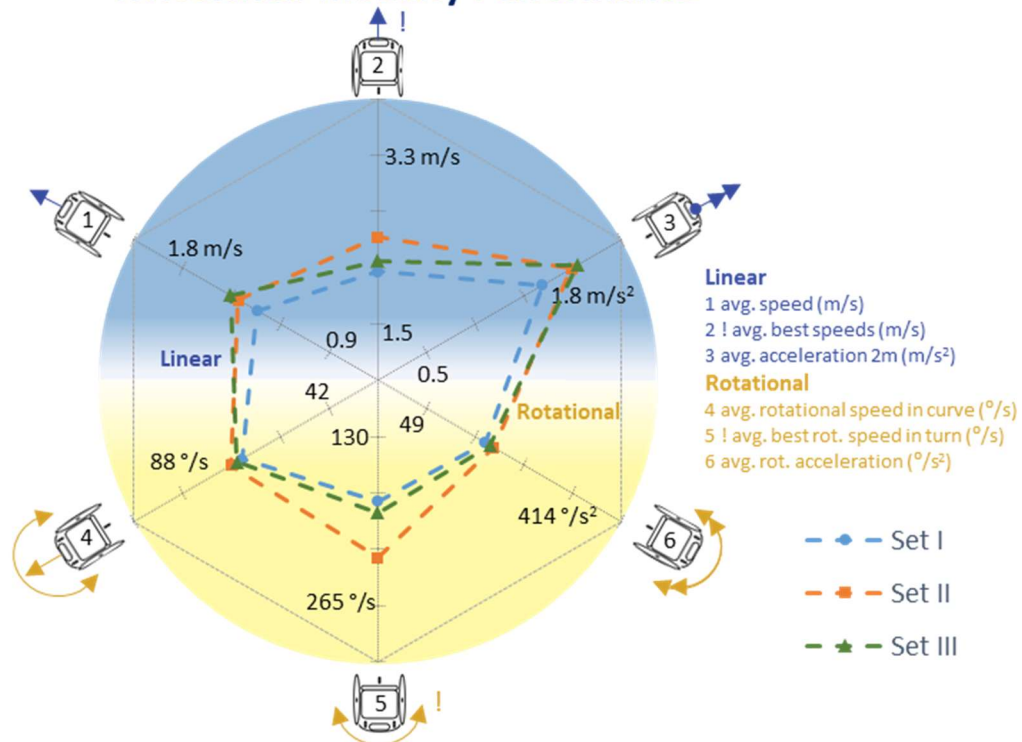


Figure 8.5: a) WMP-plot of a three set wheelchair tennis match of an international top 20 player. The first set was quite easily won, but during the second set the level of play became very close, resulting in a loss in the tie break and a loss in the final set. b) The course of the forward and rotational acceleration, plotted as average per minute for both players. The purple bars (dark) resemble the same player as the WMP plot on top, the blue (light) resemble the opponent. Set I ranged from 0 - 29 min.; set II from 30 - 110 min. and set III from 115 - 160 min. (see grey dotted lines).



In this example, the results of a wheelchair tennis athlete and his opponent are plotted, but similar plots could be made for wheelchair rugby and basketball, showing the WMP per quarter and course of a certain outcome for multiple players in a team. So, the reports could be tailored to support individual analysis during a match; during a season; during an intervention; by comparison to reference values and they could support team play by showing the results of multiple players.

The mobility performance profile per sport could also be used to direct training goals or wheelchair configuration targets, albeit that observed kinematics do not necessarily imply best possible performance, so still interpretation of the coach and athlete is needed to set individual targets. That aspect considered, it could be concluded that wheelchair basketball is the most intense sport of the three, so that might support setting up training schedules and wheelchair configuration. In wheelchair tennis, there are less abrupt movements, but more emphasis could be directed at the manoeuvrability. Finally, in wheelchair rugby, the largest differences in performance were displayed, most likely the effect of variety in impairment level. Therefore, training schedules and wheelchair configuration will most likely benefit most from an approach where impairment level is taken into account, rather than a more general sports wide approach.

#### Conclusion

The wheelchair mobility performance monitor showed performance profiles per court sport in line with the expectations, with wheelchair basketball showing highest mobility performance and wheelchair rugby the lowest. Next to the proven sensitivity for quantifying performance differences between competition and impairment level (van der Slikke et al., 2017; van der Slikke et al., 2018), this study shows its applicability across wheelchair court sports. The WMPM could support individual athletes in performance enhancement within a match or within a season, it could support coaches in monitoring players and selecting the best team composition, it could support wheelchair specialist in tuning the wheelchair configuration for best performance and it could support physical capacity based referral to the appropriate sport in the rehabilitation process.

#### Acknowledgement

The authors would like to thank all athletes participating in this research project and all coaches involved in measurement planning.

#### Conflict of interest statement

None.





# Chapter 9

## Comparison of methods for measuring mobility performance

Speed profiles in wheelchair court sports;  
comparison of two methods for measuring  
wheelchair mobility performance.

*Journal of Biomechanics*



## Chapter 9: Comparison of methods for measuring mobility performance

### Speed profiles in wheelchair court sports; comparison of two methods for measuring wheelchair mobility performance.

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#### Abstract

Wheelchair mobility performance is an important aspect in most wheelchair court sports, commonly measured with an indoor tracking system or wheelchair bound inertial sensors. Both methods provide key wheelchair mobility performance outcomes regarding speed. In this study, we compared speed profiles of both methods to gain insight into the level of agreement, for recommendations regarding future performance measurement. Data were obtained from 5 male highly trained wheelchair basketball players during match play. Players were equipped simultaneously with a tag on the footplate for the indoor tracking system (~8 Hz) and inertial sensors on both wheels and frame (199.8 Hz). Being part of a larger study on 3 vs 3 player game formats, data were collected in several matches with varying field sizes, but activity profiles closely resembled regular match play. Both systems provide similar outcomes regarding distance covered and average speed. Due to differences in sampling frequency and sensor location (reference point) on the wheelchair (for speed calculation), minor differences were revealed at low speeds (<2.5 m/s). Since both systems provide complementary features, a hybrid solution as proved feasible in this study, could possibly serve as the new gold standard for mobility performance measurement in wheelchair basketball or wheelchair court sports in general.

**Keywords:** *wheelchair basketball, activity profiles, wheelchair mobility performance, inertial sensors, indoor tracking.*

## Introduction

Quantitative assessment of an athlete's individual wheelchair mobility performance is needed to evaluate game performance, improve wheelchair settings and optimize training routines (Mason et al., 2013). Next to sport specific mobility performance outcomes, speed is one of the key performance indicators, relevant to all wheelchair sports (Burton, Fuss, & Subic, 2010; Rhodes et al., 2015; van der Slikke et al., 2016). Based on a semi-structured interview of nine elite athletes, Mason et al. (2010) identified speed as one of the key performance indicators, important for optimizing wheelchair configuration. Fuss et al. (2012) emphasises the benefits of standard speed measurements in high-performance sports with decreasing costs of technology required. On court wheelchair mobility performance research, is often based on methods that either rely on wheelchair mounted or global reference sensors. Wheelchair bound systems essentially measure wheel rotational speed to calculate forward speed, with data loggers based on reed-switches (Tolerico, Ding, Cooper, & Spaeth, 2007), potentiometers (Velocometer) (Moss, Fowler, & Tolfrey, 2003), or inertial sensors (van der Slikke et al., 2015; van der Slikke et al., 2015a). If sensors are placed in a fixed global position, wheelchair speed is measured with either laser technology (Ferro, Villaceros, & Pérez-Tejero, 2016) or radio frequency-based technology (Rhodes et al., 2014). This technical note describes the comparison between two common systems for performance measurement in court sports, namely the inertial sensor-based wheelchair mobility performance monitor (WMPM, (van der Slikke et al., 2015) and the global reference based indoor tracking system (ITS), (Rhodes et al., 2014).

Inertial sensor-based methods like the WMPM allow for easy and accurate measurement of wheelchair mobility performance, but provide no information about absolute field position. Indoor tracking systems provide positional data, enabling tactical team analyses, but lack the option to calculate higher order outcomes like acceleration, due to sample frequency restrictions. In this study, we compared outcomes of both methods regarding speed, to gain insight into the level of agreement between devices.

## Methods

### *Participants & instrumentation*

Five male, highly trained wheelchair basketball players (age:  $20 \pm 1$  years; playing experience:  $7 \pm 2$  years, IWBF classification: 1.0, 2.0, 3.0, 3.5 & 4.5) volunteered to participate in the study. Their wheelchair mobility performance was monitored using an ITS (Ubisense,  $\sim 8$  Hz) with a tag positioned on the footplate and simultaneously with three inertial sensors (Shimmer3, 199.8 Hz) on wheels and frame (WMPM) of their own customised sports wheelchairs. Since the objective was to compare existing technologies, procedures and settings used for ITS and WMPM were in line with previous research.

### *Measurements and setup*

Being part of a larger study on wheelchair basketball game innovations (Mason et al., 2017), measurements (6 times 10 min.) were performed during different 3 versus 3 game formats (full court, half court and a modified court length of 22 m). Six ITS sensors were located around the perimeter of a regulation-size wheelchair basketball court (28 x 15 m). The sensors were positioned at each of the four corners of the court, with two additional sensors positioned at the half-way line. Each sensor was mounted on an extendable tripod, elevated approximately 4 m high. The digital signal processing of the ITS was originally optimised for position accuracy, using a 3-pass sliding-average filter with a window width proportional to the tag frequency (Rhodes et al., 2014). In the ITS processing for this study, a five point ( $\sim 0.625$  Hz) sliding average filter was applied to the raw position data of the tag. The tag was positioned at the footplate to ensure best reception by the sensors, as described by Perrat et al. (Perrat, Smith, Mason, Rhodes, & Goosey-Tolfrey, 2015). For the wheelchair mobility profile, speed is derived from the filtered position data. Note that the outcomes of the ITS describe the motion of the tag mounted on the footplate, whereas the WMPM describes the movement of the wheelchair frame centre in-between both main wheels, so the reference points on the wheelchair differ (Figure 9.1). For the WMPM speed calculation is based on wheel rotation derived from the wheel sensors, with additional skid correction algorithm (van der Slikke et al., 2015a). Heading direction is based on the inertial sensor mounted to the frame (van der Slikke et al., 2015). Due to the shared frequency bandwidth between multiple player tags in the ITS, the sample frequency varied slightly around 8Hz. Sample timestamps were utilized to resample up to the WMPM frequency (linear interpolation, Interp1, Matlab). Given the absence of hardware synchronisation options, a cross-correlation of speed signals was used for post synchronisation of systems (Li & Caldwell, 1999).

### *Data processing*

For each of the six measurements per player (10 min. match play), distance covered, speed and time in six fixed speed zones (see Table 9.1) was calculated. The speed zone thresholds are enclosed in the ITS method, originally based on the research regarding wheelchair rugby (Rhodes, 2015) and wheelchair tennis (Sindall et al., 2013).

The single tag per wheelchair for the ITS does not allow for determination of heading direction of the wheelchair, so no distinction between forward and backward movement is made. The WMPM does differentiate between directions, but to allow for proper comparison with the ITS, *absolute* values of speed were used. To gain insight in the relationship between ITS and WMPM across speeds, the average value of both systems categorised by 0.05 m/s increments, were plotted against each other.

Although the WMPM reference point at the frame centre seems preferable over a reference point at the foot plate, the ITS position outcome does not allow for recalculation of an alternative point on the wheelchair frame, since heading direction is unknown. It was however

possible to re-calculate WMPM outcomes to a foot plate reference point and with filtering similar to the ITS procedure. The WMPM heading direction and the measured distance between rear axle and foot plate was used to calculate the speed of the footplate reference point (see Appendix I). This speed signal was low-pass filtered (0.5 Hz, 2<sup>nd</sup> order Butterworth) and used to calculate the alternative outcomes, named WMPM2. This is not the preferred outcome of the WMPM, but does allow for the most optimal comparison of calculated displacement and speed.



Figure 9.1: Wheelchair measurement setup, with the Ubisense tag (ITS) mounted on the footplate and the Shimmer3 inertial sensors on frame and wheels. The reference point for the ITS ( $R_{ITS}$ ) is the same as the tag, whereas the reference point for the WMPM ( $R_{WMPM}$ ) is the frame centre. The WMPM2 reference point is in the middle of the footplate, so close to the  $R_{ITS}$ .

## Results

The average distance calculated per 10 min. game time was 882.3 m for the ITS, 837.8 m for the WMPM and 883.4 m for WMPM2 (see Table 9.1). Differences in calculated distance per 10 min. match play, between ITS and WMPM ranged from -7.6% to 6.4% and between ITS and WMPM2 from -7.6% to 7.3%. The root mean square differences (RMSDs) were calculated based on the comparison between the resampled ITS speed signal versus the WMPM speed (RMSD of 0.41 m/s) and the WMPM2 speed (RMSD of 0.33 m/s). The differences in percentage time spent within the six fixed speed zones varied from 0.1 – 15.7 between ITS and WMPM and 0.0 – 9.0 between ITS and WMPM2 (see Table 9.1). Figure 9.2 shows a typical example (20s game play) of the speed of a wheelchair as measured with the different systems. The average ITS corresponding speed per 0.05m/s speed category of the WMPM is shown in Figure 9.3.



Table 9.1: Average speed and distance related outcomes of the five athletes in six measurements. Data of the indoor tracking system (ITS) are shown in the middle, the Wheelchair Mobility Performance Monitor (WMPM) outcomes are shown on the left and the adjusted WMPM2 shown on the right. Columns in-between show the average differences and standard deviations (SD) of the differences between methods. The lower part shows the percentage time spent in the different speed zones, as adopted from Mason et al. (2014).

		WMPM	<i>difference</i>	<i>SD</i>	ITS	<i>difference</i>	<i>SD</i>	WMPM2	
Distance		837.8	-2.6%	3.2%	882.3	0.1%	3.3%	883.4	
Speed (m/s)	average	1.30	-2.6%	3.2%	1.37	0.1%	3.3%	1.38	
	RMSE		0.41	0.060		0.33	0.072		
Speed (m/s)	Zone	0 - 0.5	22.4%	13.7	5.1	8.7%	5.7	4.5	14.4%
		0.5 - 1.5	37.9%	-15.7	5.9	53.6%	-9.0	5.1	44.6%
		1.5 - 2.5	29.3%	-0.1	3.2	29.4%	2.0	2.8	31.3%
		2.5 - 3.0	6.6%	1.0	1.4	5.5%	0.9	1.4	6.4%
		3.0 - 3.5	2.8%	0.7	0.9	2.1%	0.4	0.9	2.5%
		3.5+	1.0%	0.3	0.7	0.7%	0.0	0.7	0.7%

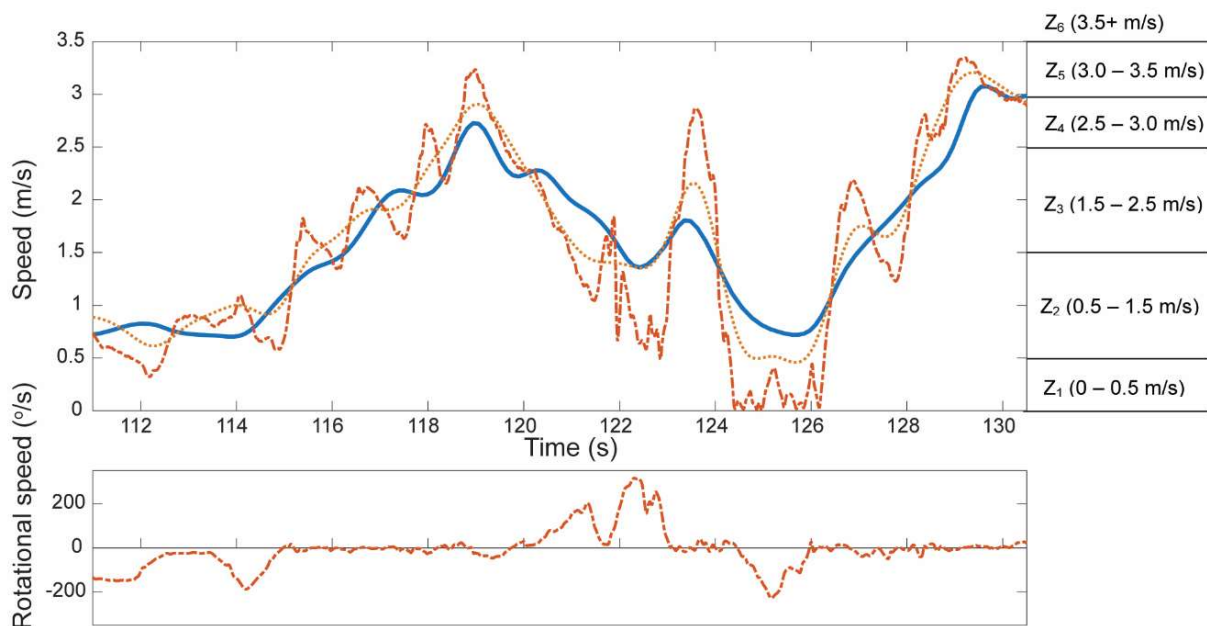


Figure 9.2: The top graph shows a typical example of several seconds of the speed signal by the ITS (solid), WMPM (dashed) and recalculated WMPM2 (dotted). The differences between ITS and WMPM show in the details, the WMPM speed signal for example clearly shows each push (112 – 119s), whereas the ITS only shows minor variations in that time frame. Furthermore, deviations between speed patterns occur in moments of turning, indicated by the rotational speed in the bottom graph (120 – 123s & 124.5 – 126s). During a turn on the spot (124.5 – 126s), the WMPM shows no speed, whereas the ITS shows minimal speed of the foot plate reference point. The WMPM2 speed with footplate reference and adjusted filter frequency shows less prominent deviations to the ITS speed pattern.

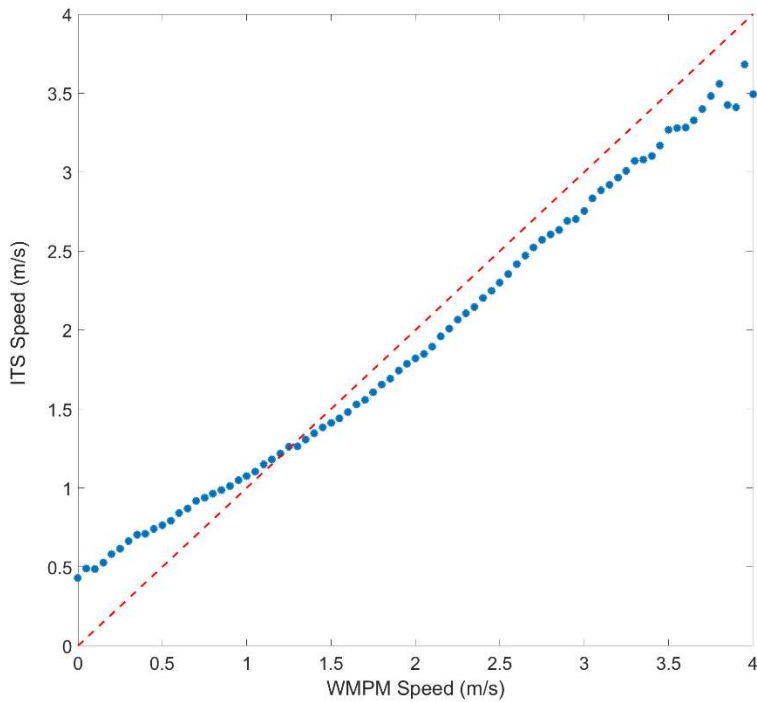


Figure 9.3: The ITS speed plotted against the WMPM speed. Per increment of 0.05 m/s the average of all corresponding ITS data points was calculated (80 averages / dots). The graph shows higher values for ITS (above the dashed line) at below average speeds, and slightly lower values at above average speeds (below dashed line), compared to the WMPM.

## Discussion

In general, both systems provide quite similar speed data, but the method features do account for some typical deviations. The difference in reference point on the wheelchair (footplate vs. frame centre) affected the calculated speed and distance slightly ( $\leq 2.6\%$ ). In the ITS, turns on the spot (turning without displacement of the frame centre) will cause a displacement equal to the circumference path described by the footplate, whereas the WMPM will not calculate any displacement at the same time. Since the ITS only provides information on tag position and not on heading direction, it is impossible to calculate the speed and distance covered of a different reference point on the wheelchair. To attain a fair comparison, it is however possible to adjust the WMPM outcomes to a reference point near the footplate. Once adjusted, systems provide very similar distance and average speed data ( $\leq 0.1\% \pm 3.3\%$ ), although still individual differences up to 7.6% occur. The RMSD of 0.41 m/s for the WSPM speed and 0.33 m/s for the WMPM2 speed seem acceptable for this type of measurements, where speeds range from 0 - ~5m/s in match play (van der Slikke et al., 2016). Differences in instantaneous speeds as expressed in the RMSD, do not influence the average speeds calculated, but might affect calculated maximal speeds. The position of the reference point causes a very low percentage of time in the lowest speed zone ( $<0.5$  m/s) for the ITS and WMPM2, because when not moving forward, often turns on the spot still cause some speed (see Figure 9.2, time 124.5 - 126s). The restricted sample frequency of the ITS, requires low-pass filtering with a very low cut-off frequency ( $\sim 0.625$  Hz), drawing the speed signal towards

the average, so with more time assigned to the corresponding average speed class (0.5 – 1.5 m/s, see Figure 9.2). The abovementioned effects also show in Figure 9.3, with ITS values higher than WMPM in speeds below ~1.5 m/s, due to the tag position and rotations, and ITS values slightly lower than the WMPM in speeds over ~1.5 m/s, due to more severe low-pass filtering with the ITS. These results provided an insight to what extent research outcomes obtained with both methods are interchangeable. For distance, average speed and above average speeds zones (> 1.5 m/s), both methods provide similar outcomes. Speed profiles show higher ITS values for below average speeds and slightly lower values for above average speeds, compared to the WMPM.

Although match play settings for the measurements deviated slightly from regular 5 vs 5 match play at regular court settings, the activity profiles did closely resemble the typical elite level performance. The average speed in the measurements was 1.37 m/s (1.3 for the WMPM), which is only slightly lower than reported in literature for elite level wheelchair basketball match play 1.48 m/s (Spörner et al., 2009) and 1.57 m/s (van der Slikke et al., 2016). Also, peak speeds were a bit lower than reported earlier in elite wheelchair basketball, 2.19 m/s compared to 2.95 m/s (van der Slikke et al., 2016). The somewhat lower average and peak speed could be explained by the reduced court sizes (half court and modified 22m court length) in part of the measurements. Those dimensions might also have led to an increase in rotations, magnifying the differences between systems due the difference in reference point. Regular match play with higher average speed and less rotations, is expected to positively influence method agreement.

#### Conclusion

For applied sports research, ease of use and fast turnaround of feedback are crucial in any method. Both measurement systems meet those demands and outcomes proved interchangeable to a great extent. The type of method used for future research is depending on the research question, with a focus on field position (ITS) or acceleration profiles (WMPM). The ITS provides information on field position, so enables wheelchair mobility performance analysis split by game specific characters (e.g. offence-defence, location to the bucket and heat maps). The WMPM provides more detailed kinematic data, allowing for analyses regarding e.g. accelerations, rotations and push characteristics (van der Slikke et al., 2016). For the most comprehensive approach, this study proved the feasibility of a hybrid solution incorporating both methods, hence providing the best of both worlds and possibly serving as the new standard for mobility performance in court sports.

#### Conflict of interest

None.

## Acknowledgement

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## Appendix I

The frame centre displacement in the WMPM is based on the average wheel speed derived from wheel rotational speed and wheel circumference (van der Slikke et al., 2015). This calculation results in a reference point in the middle between both main wheels, thus the middle of the camber bar. To recalculate the speed of a reference point on the footplate, the speed of this point due to rotations with regard to the original reference point, is added. See Equation 1, with the recalculated speed ( $Speed_{WMPM2}$ , [m/s]) based on the original speed ( $Speed_{WMPM}$ , [m/s]), the frame rotational speed ( $RotSpeed_{WMPM}$ , [°/s]), the distance between rear axle and footplate ( $d_{a-f}$ , [m]) and the sample frequency ( $fs$ , [Hz]).

$$Speed_{WMPM} = \sqrt{\left(\frac{Speed_{WMPM}}{fs}\right)^2 + \left(\sin\left(\frac{RotSpeed_{WMPM}}{fs}\right) \times d_{a-f}\right)^2} \times fs \quad (1)$$

A close-up, low-angle photograph of a wheelchair's metal frame. The frame is made of polished, reflective metal tubes that create a complex, geometric pattern of lines. In the lower-left quadrant, a white, rectangular electronic device is mounted on the frame. It has a prominent orange circular button on its top surface and a black strap or sensor attached to its bottom. The background is a bright, out-of-focus white, which makes the dark metal frame stand out. The lighting is dramatic, highlighting the metallic sheen and the sharp angles of the frame.

# Chapter 10

## Push characteristics in wheelchair sprinting

Push Characteristics in Wheelchair Court Sport  
Sprinting. *Procedia Engineering*



## Chapter 10: Push characteristics in wheelchair sprinting

### Push Characteristics in Wheelchair Court Sport Sprinting

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#### Abstract

Short sprints are important components of most wheelchair court sports, since being faster than the opponent often determines keeping ball possession or not. Sprinting capacity is best measured during a field test, allowing the athlete to freely choose push strategies adapted to their own wheelchair setting, physical ability, classification and speed changes during a sprint. The key test outcome is sprint duration, but there are various ways to accomplish the same sprint time. So, can different push strategies be identified in a wheelchair sport and how do they relate to athlete level/classification and wheelchair configuration? These relationships were investigated by field tests of 30 male wheelchair basketball athletes during a 12-meter sprint in their own wheelchair. A recently developed method for ambulatory measurement was used to calculate wheelchair kinematics (van der Slikke et al., 2015), providing outcomes on displacement, speed, acceleration and pushes. Additionally, maximal isometric push force was recorded and rear seat height was noted. Within the measured athletes, internationals were expected to be faster due to a better physical training status and technique, allowing them to sprint with fewer (but more powerful) pushes. Likewise, athletes of higher classification were expected to be faster due their superior physical capacity, but the effect on the number of pushes used was not that evident. Video analysis was added to validate push detection of the ambulatory measurement system. Mutual correlations and competition level differences of sprint characteristics were calculated. General Linear Models (GLM) were drawn to determine the effect of competition level and classification on sprint time and number of pushes.

In the overall dataset sprint characteristics did not correlate significantly with classification, but if split by competition level, there were significant correlations with sprint time ( $r=-0.715$ ,  $p=0.006$ ) and number of pushes ( $r=-0.647$ ,  $p=0.017$ ) in the national level athletes. Sprint time, number of pushes and isometric push force differed significantly between national and international level wheelchair basketball athletes. Competition level showed to be a significant ( $p<0.05$ ) factor in univariate GLMs for sprint time and number of pushes, whereas classification did not. The interaction of competition level and classification as a factor in univariate GLMs was significant.

As hypothesized, international level athletes were faster with fewer pushes, even though their higher average seat height was less optimal for propulsion (Mason et al., 2013). The interaction effect of competition level and classification in the GLM indicates that the effect of classification on sprint time and number of pushes is different between competition levels. Indeed, in the national level athletes there was a clear relationship between classification and sprint time / number of pushes, but not in internationals. This difference is pointing at a more professional level of wheelchair configuration or better technique of the international athletes regarding sprint performance. Given the correlation between seat height and classification, the seat height of lowly classified athletes seemed optimized for sprinting, whereas seat height of highly classified athletes with already adequate sprinting capacity was optimized for upward reach. Future research based on larger groups with more even distribution over classifications could provide more solid models and reveal more detailed insight in push strategy efficacy. Given the proven reliability of the inertial sensor-based method (van der Slikke et al., 2015) and the proven reliability for push detection in sprinting, this research could well be performed using this easy to use ambulatory method. Although more challenging than well controlled experimental research, the field-based setting in this research revealed additional information not only describing the relation between wheelchair setting and performance, but also describing its practical applications if other game demands were taken into account. The results of this approach is believed to assist athletes, coaches and wheelchair experts in decision making concerning wheelchair configuration and athlete training.



## Introduction

In wheelchair sports, athlete and wheelchair could be considered as one functional unit allowing overall performance improvement by athlete training, wheelchair optimization and perfecting the interaction (Mason et al., 2013). The ability to perform a sprint as fast as possible is an important factor in most court sports, since it determines the opportunity to take initiative in the next action. But by optimizing for sprint capacity, there often is a trade-off with other performance aspects, such as upward reach or stability. Therefore, athletes and wheelchair experts often optimize wheelchair configuration based on athlete capacity in conjunction with specific roles in the team play. Since it is difficult to weigh those demands and their interaction, more insight in the relationship between athlete/wheelchair characteristics to sprint performance could underpin choices in wheelchair adjustment or athlete training.

Effects of wheelchair configuration on wheelchair performance are well described by publications based on experimental research (Boninger et al., 2000; Masse et al., 1992; van der Woude et al., 1998; van der Woude, Veeger, Dallmeijer, Janssen, & Rozendaal, 2001; Vanlandewijck et al., 2001) often utilizing an ergometer, treadmill or experimental wheelchair. To include the interaction between athlete and wheelchair configuration, Mason (Mason et al., 2013) recommends quantitative research with wheelchair athletes to identify optimums in configurations. With that goal in mind one needs research data gathered in circumstances that are close to the specific sport setting, with athletes in their own wheelchairs and in a field-based test. This paper describes the relationships found between wheelchair settings and sprint performance based on a 12-meter sprint test of 30 male wheelchair basketball athletes. Within these athletes, internationals were expected to sprint faster and with fewer pushes to cover the same distance, as a result of their superior physical training status and technique, compared to national level athletes. In the same way, higher classified players with more physical capacity were expected to be faster but with an indefinite difference in number of pushes used in the sprint.

## Methods

### *Setup and participants*

Thirty elite level wheelchair basketball athletes (see Table 10.1) performed a series of tests, including a 12-meter sprint in their own sports wheelchair. Athletes were measured in training sessions and during the Euro Cup 4 tournament at Papendal (NL) 2015. On each wheelchair three inertial sensors (Shimmer3, Shimmer Sensing) were mounted, in accordance with the method described by van der Slikke (van der Slikke et al., 2015; van der Slikke et al., 2015a). Custom made clips allowed for easy application on each wheelchair,



Figure 10.1: Sensor mounting locations on the wheelchair

with one sensor on each wheel hub and one centrally placed on the frame. Acceleration and rotational speed data were collected at 200 Hz and transmitted by Bluetooth to a laptop running Matlab with the Shimmer instrument driver. The sprint tests were performed in regular athlete training facilities. Prior to the sprint test athletes were asked to carry out a warming up and inflate their tires to 7 bars. In addition to the sprint test, maximal isometric forward push force was measured with the footplate of the wheelchair attached with a rope to a force gauge (Mecmesin AFG 1000N) mounted to a measurement plateau on which the wheelchair was stationed. After a trial run, athletes were asked to employ maximal push force for at least 3 seconds in five different hand positions on the rim (-30°; TDC; +30°; maximal forward; self-chosen position). Wheelchair dimensions were measured, including wheel and rim diameter, camber angle, track width and rear seat height.

The study was approved by the ethical committee of the Department of Human Movement Sciences (ECB-2014-2) Vrije Universiteit Amsterdam. All participants signed an informed consent after being informed on the aims and procedures of the experiment.

Table 10.1: Athlete and wheelchair data

Group	Number	Nationality	Age (y)	Seat height (m)	Classification							
					1	1.5	2	2.5	3	3.5	4	4.5
National	13	NLD	24.9	0.55	2		1		2	1	5	2
International	17	NLD, GBR, TUR, ESP, SWE, ITA, CYP	26.0	0.61	2	1	1	4	3		2	4
Overall	30		25.6	0.59	4	1	2	4	5	1	7	6

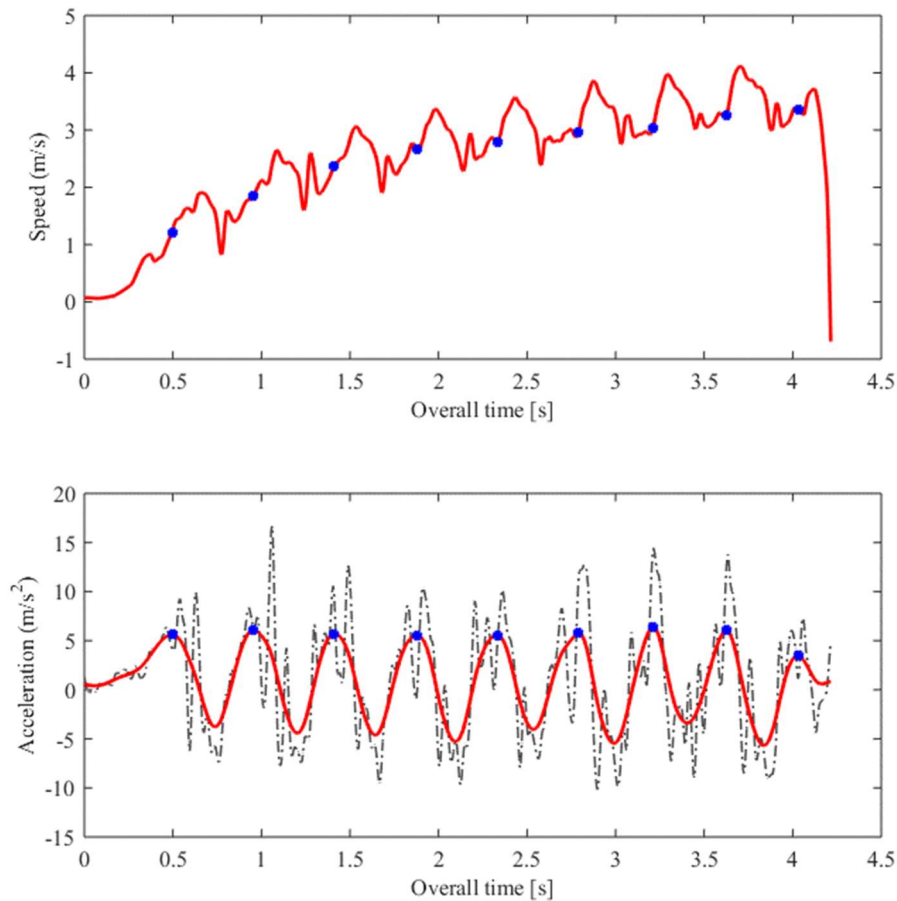


Figure 10.2: Typical example of the speed (upper graph) and forward acceleration (lower graph) during a 12-meter sprint. The dashed line shows the unfiltered acceleration data and the solid line the filtered data and detected pushes (dots).

### *Push detection*

In addition to the previously described method for calculation of wheelchair kinematics (van der Slikke et al., 2015), a push detection algorithm was developed based on the forward acceleration of the wheelchair. The main forward accelerations were considered to be due to active athlete pushes, so the algorithm was shaped to distinguish those peaks from other fluctuations in the forward acceleration signal. A frequency spectrum (Matlab, “periodogram”) was made with the most prominent frequency over 1.2 Hz assumed to represent the mean push frequency. The forward acceleration was low pass filtered by 1.5 times that frequency and subsequently acceleration peaks were identified (Matlab, “findpeaks” with a minimal peak height and prominence of 0.5 acceleration signal standard deviation and a peak distance of 0.67 times the assumed mean push frequency). Figure 10.2 shows the pushes detected in a typical example of the forward acceleration in a 12-meter sprint.

Video observed pushes were used as gold standard for comparison with the sensor detected pushes. Three post-measurement synchronized video camera footages were used to register pushes. A push was defined as full hand-rim contact until rim release. So, if the final push was followed by braking without rim release, it was discarded.

### *Outcomes*

Inertial sensor-based wheelchair kinematics were used to calculate sprint specific outcomes. The start time of the sprint was determined by the first moment of speed over a threshold (0.05 m/s) and the stop time of the sprint as the first moment of speed below the threshold after the required displacement. The maximal speed was determined by the maximal speed value in the 12-meter sprint, typically just before braking. The number of pushes was based on the push detection as described in the previous paragraph, with also several derived outcomes calculated like average push time, push frequency and acceleration per push. For maximal isometric force the highest 3 second average of the five pushes on the measurement plateau was taken.

### *Statistics*

All outcomes were tested with the Kolmogorov-Smirnov test for normal distribution. To rate the reliability of the sensor-based push detection, its outcomes were compared to the video observed pushes using the ICC (absolute agreement) method.

Relationships between athlete/wheelchair characteristics and sprint outcomes were determined with a Pearson correlation, except for the correlation with classification which was determined by a Spearman test. Differences in sprint characteristics between competition level outcomes were tested with a T-test. Given the classification differences in measured athletes per competition level, the effect of classification on sprint characteristics was tested by building a univariate General Linear Model (GLM) and determining the influence of each factor on the explained variance.

### *Results*

Data were collected without any sensor data reception loss. In 27 cases, measurement circumstances allowed for video analysis and video data were used to register the number of pushes. Isometric maximal force was measured in 29 athletes, with one wheelchair being too wide for the measurement plateau.

All athlete/wheelchair data and sprint characteristics were distributed normally, allowing for parametric statistics except for classification. The only significant Spearman correlation between classification with any of the other characteristics was the correlation with seat height (overall:  $r=0.555$ ,  $p=0.001$ ; nationals:  $r=0.677$ ,  $p=0.011$ ; internationals  $r=0.668$ ,  $p=0.003$ ). The ICC for video observed and sensor-based detected pushes was 0.946, with 3 times (11%) 1 push over detection and in 2 times (7%) 1 push under detection (by 7.97 push on average per 12-meter sprint). Significant correlations between athlete/wheelchair and sprint characteristics are displayed in Table 10.2. Most sprint characteristics had high mutual correlations, but a bifurcation could be identified relating to outcome parameters concerning speed/time on the one hand and push related outcomes on the other hand. So, for further analysis “sprint time” and “number of pushes” were used, since they correlated moderately ( $r=0.447$ ,  $p=0.013$ ) and seemed to measure different aspects of sprint characteristics.

**Table 10.2: Significant ( $p < 0.05$ ) Pearson correlations between sprint characteristics and athlete/wheelchair data within the complete dataset.**

Variables		Pearson
Sprint time	x Nr. of pushes	.447
Sprint time	x Max. speed	-.856
Sprint time	x Max. iso force	-.473
Max. speed	x Nr. of pushes	-.450
Max. speed	x Seat height	.371
Max. speed	x Max. iso force	.591
Seat height	x Max. iso force	.418

**Table 10.3: Differences between mean athlete/wheelchair and sprint characteristics per competition level. With significant differences indicated by the italic p value in the right column.**

Variable	National		International		T-Test
	Mean	SD	Mean	SD	p
Classification	3.3		3.0		n.a.
Age (y)	24.8	12.1	26.0	7.7	0.510
Seat height (m)	0.56	0.07	0.61	0.07	0.072
Max iso force (N)	470	166	574	90	0.041
Sprint time (s)	4.10	0.40	3.67	0.33	0.003
Nr. of pushes	8.6	1.0	7.5	1.7	0.035

**Table 10.4: General Linear Model outcomes with significance level ( $p$ ) of the model, R squared ( $R^2$ ) and R squared adjusted ( $R^2$  adj.) for the number of explanatory terms.**

Variabile	Factor1	Factor2	p	$R^2$	$R^2$ adj.
Sprint time			0.003	0.268	0.242
Nr. of pushes	level (2)		0.035	0.149	0.118
Max iso force			0.041	0.145	0.231
Sprint time			<i>0.165</i>	<i>0.349</i>	<i>0.142</i>
Nr of pushes	class (8)		<i>0.084</i>	<i>0.403</i>	<i>0.213</i>
Max iso force			<i>0.110</i>	<i>0.395</i>	<i>0.194</i>
Sprint time		class	0.011	0.566	0.401
Nr of pushes	level (2)	(8)	0.027	0.518	0.335
Max iso force			0.027	0.533	0.348
Sprint time	level *		0.026	0.664	0.427
Nr of pushes	class		0.008	0.721	0.524
Max iso force			0.050	0.646	0.380
Seat height	level (2)		0.072	0.111	0.079
Seat height	level (2)	class	0.006	0.599	0.446

Although competition level groups were not identical in athletes per classification, on average the number of low-high classified athletes was similar (see Table 10.1 & 10.3). Age distribution was similar in both groups and although not significant, international athletes appeared to have a higher average seat height (Table 10.3). Indeed, if classification was taken into account as an additional fixed factor, competition level and classification both appeared significant ( $p < 0.05$ ) in the GLM for seat height (Table 10.4). Measured outcomes showed that significantly more isometric push force was generated by the international compared to national level athletes and that they were faster with fewer pushes on the 12-meter sprint.

GLMs were built for sprint time, number of pushes and maximal isometric push force with the factors competition level and classification (Table 10.4). Level as a factor produced significant models ( $p < 0.05$ ) for all outcomes, where solely classification produced none. If only main effects of competition level and classification were included in the model, significant models were produced with approximately double the explained variance ( $R^2$ ) compared to solely level as a factor. The interaction between both factors alone, also showed significant in GLMs for all outcomes.

## Discussion

In wheelchair sports it is the interaction between wheelchair and athlete that enables propulsion and sporting movements, outlining wheelchair mobility performance (Goosey-Tolfrey & Leicht, 2013). To gain insight in this relationship in the most ecological valid way, this research comprised field testing athletes in their own wheelchair in a competition like setting. Using this method, athletes were tested with their wheelchair settings not just optimized for sprinting, but also with other demands in mind based on sport specific field positions. Sprinting capacity could be described with a variety of properties, such as acceleration from standstill, average speed, maximal speed, number of pushes, push frequency and acceleration per push, but they partly measure the same aspects of the sprint. Based on mutual correlations, two different aspects were acknowledged namely the sprint time as measure for the sprint goal and the number of pushes as a factor of push strategy.

As expected, competition level was an important factor in sprint performance, with international level athletes being faster with fewer pushes on average, despite the (not significantly different) higher average seating position compared to national level athletes. Shorter sprint times with fewer pushes could be achieved with either pushes with increased acceleration (more force) or prolonged acceleration (push force in a longer trajectory) per push. The correlation between maximal isometric push force and sprint time ( $r=-0.473$ ) supports that part of the increased acceleration per push was due to increased push strength. The magnitude of isometric push force (as measured in this configuration) in turn can be altered by increased physical training (athlete) or changes in wheelchair configuration.

The effect of classification (physical capacity) on sprint performance was clear in the national level group, given the Spearman correlations with sprint time ( $r=-0.715$ ,  $p=0.006$ ) and number of pushes ( $r=-0.647$ ,  $p=0.017$ ). Yet in the international level group this relationship was not uncovered, pointing at other aspects that counter acted the sprint performance differences due to classification. Since sprint performance is only one game aspect, wheelchair configurations could be set with alternative goals in mind. Given the correlation between classification and rear seat height the effect of classification differences could have been partly undone by lowering the seat for lowly classified athletes with a positive effect on wheelchair sprint performance as described by Mason et al. (2013). So, this correlation could be interpreted as an optimization in wheelchair settings towards sprint performance at the expense of upward reach. This finding is in line with the common practice to allocate lowly classified athletes in a more defensive game role, with most game demands on speeds and less focus on upward reach. In international athletes, average seat height is significantly higher (if corrected for classification), so with presumably more focus on upward reach.

No reliable GLMs for sprint outcomes could be built with only classification as a fixed factor (Table 10.4), but if competition level was added, R squared values for sprint time and number

of pushes raise to  $R^2=0.566$  and  $R^2=0.518$  respectively. As a predictor for future measurements, the adjusted  $R^2$  shows an explained variance of 40.1% for sprint time and 33.5% of the number of pushes if classification and competition level were regarded. The construction of this model was affected by two single outliers per classification and competition level. Since the classification of athletes was not evenly distributed over competition level in this dataset, grouping classifications did not improve the GLM. But given the outliers and the model prediction improvement if interaction of competition level and classification is included, it is likely that the GLM improves substantially if the “gaps” in athlete classification in this dataset are filled with additional measurements.

Study results show a high correlation ( $ICC = 0.946$ ) between the sensor-based push detection and video observed pushes, with maximal 1 push miss detection in a 12-meter sprint. It was concluded that the sensor detection could be applied with confidence for distances of at least 12-meters. The complexity of the relationship between wheelchair performance and wheelchair/athlete characteristics requires detailed outcomes to ensure the usability of a field test, pinpointing the need for a reliable ambulatory method (van der Slikke et al., 2015) for measuring wheelchair mobility performance including push detection.

This field study underpins the challenge of investigating the relationship between athlete, wheelchair setting, their interaction and wheelchair mobility performance. Research with more isolated test settings (Boninger et al., 2000; Masse et al., 1992; van der Woude et al., 1998; van der Woude et al., 2001; Vanlandewijck et al., 2001) already proved relationships in aspects of wheelchair configuration with performance, but under actual competition conditions the number of influencing factors involved is substantial. Still, already within this limited dataset, trends were where spotted, pointing out the relative importance of factors in optimizing the wheelchair/athlete combination for sprint performance. Enlarging the current data set might allow for better quantification of the influence of those factors, if more solid GLMs could be built. Given the easy to use measurement method with the push detection turning out to be reliable, this is a feasible future goal. With the collected data, also other aspects of wheelchair mobility performance, like manoeuvrability could be investigated, providing athletes, coaches and wheelchair experts with functional information for their considerations to optimize each athlete/wheelchair for the game demands.

Results show that in general athletes with less physical capacity (low classification) adjust their wheelchair with a relative low seat height, to allow for prolonged and more powerful pushes. Given the absent correlation between sprint time / number of pushes and classification, this adaptation is more effectively done in international level wheelchair basketball athletes and/or in that group other performance goals have higher priority.

#### Acknowledgements

The authors would like to acknowledge all athletes participating in the research and colleagues and students Human Kinetic Technology who assisted in carrying out the measurements.





# Chapter 11

General discussion





## Chapter 11: General discussion

The aim of this thesis was to enhance wheelchair sports, for which a reliable and easy to use method was developed, providing key kinematic outcomes of wheelchair basketball in an understandable way: The Wheelchair Mobility Performance Monitor (WMPM). The WMPM showed its value in match and field test measurements across wheelchair sports, providing new insights and foundation for further professionalisation of wheelchair court sports. For future use, the methods developed are not restricted to court sports alone, but could be employed for all types of wheeled mobility monitoring, like in other wheelchair sports or daily wheelchair use.

Out of the lab!

The fundamental concept during this thesis was to “get out of the lab, on to the court”. This concept is important for all research aiming at ecological validity, but of even greater importance in wheelchair sport related research, given the heterogeneity of the population. General principles regarding wheelchair configuration and performance have been studied before (van der Woude, Veeger, Rozendal, & Sargeant, 1989; van der Woude et al., 2001; van der Woude et al., 2009), but mostly with able bodied subjects in conditions that were quite different from sport practice. To be of direct use to the sport, athletes themselves need to be measured in their own wheelchair, in a sport specific setting and preferably almost non-stop, during match play and training.

A reliable and easy to use inertial sensor-based method was developed to measure wheelchair mobility performance, a crucial step in attaining the overall objective of developing such a system for sport practice use. Although initiatives commenced to develop the method into a product ready for the market, those concepts did not pass the prototype stage. The development of a consumer product seems feasible, and is foreseen in future projects, but has not been achieved yet. The method optimisation by adding a wheel skid correction clearly improved the quality of the outcomes, yet it is disputable if that level of accuracy is needed for the more general outcomes as used in the wheelchair mobility performance monitor. For a consumer product, the ease of use and costs might prevail over accuracy, resulting in a reduction of sensors used. If the wheel skid correction algorithm is dropped, a two-sensor solution (one on a wheel and one on the frame) conveys for calculation of all WMP outcomes. The final step to a consumer product requires reduction of costs, by using cheaper sensors or the development of a dedicated sensor set. Furthermore, it requires additional development of a consumer interface of the analysis software. Currently all analysis is done in Matlab®, but algorithms developed could also be programmed in alternative software platforms. Given the ongoing opportunities for development, especially once more performance data (big data) are available, the most tempting solution would be a cloud-based analysis platform across all devices used, that outputs the individual results to the end user. Those individual results could be displayed on an interactive performance analytics dashboard, that could be configured

based on the athlete characteristics, like the sport, training goals and competition level. But alternatively, the same dashboard could be used by the coach as well, showing multiple player performance feedback.

#### Wheelchair Mobility Performance quantified

In applied research, there is a constant search for balance between attaining a meaningful level of detail, while keeping the amount of information manageable for athletes and coaches. The developed method could generate an immense volume of output parameters regarding wheelchair kinematics. The key was to reduce that volume without losing essential information. The selection of six outcomes seem to well represent wheelchair mobility performance in wheelchair basketball, advancing to both scientific and athlete requirement. For future use, a layered structure seems conceivable, with the six outcomes as top layer and more detailed outcomes per aspect if wished for. At this stage however, more emphasis is directed at adoption of the method as it is. Once athletes and coaches are familiar with these outcomes, the demand for more detail might arise naturally.

Next to the method and the outcomes used, it is important to consider the circumstances under which the wheelchair mobility performance is determined. It is shown that match specific factors have an effect on the performance, based on factors like the opponent level or the field position of the athlete. To get insight in the maximal level of mobility performance, a measurement during sport specific field test is required. For wheelchair basketball such a test is developed and tested for reliability. Given its reliability and sensitivity to change, the wheelchair mobility performance monitor in combination with the field test is regarded as a suitable evaluation tool for interventions in training routine or changes in wheelchair settings.

Although applicable for all wheelchair court sports, the selection of outcomes and the developed field test were initially directed at wheelchair basketball. For similar application in other wheeled sports, additional research and development is wished for. For wheelchair rugby, the selection of outcomes will be comparable to basketball, but for wheelchair tennis other key features closely related to game play, might pop-up. Wheelchair kinematic outcomes that closely relate to skill might appear of greater importance than those related to endurance. So, aspects like position on the court or the stroke type might be important to take into account. Furthermore, calculated features are dependent on sports characteristics, like the average speed, which are known to differ between sports.

#### Enhance wheelchair sports

To truly enhance wheelchair sports, a new method should meet the demands of user friendliness and to be of additional value, to ensure broad adaptation and sustainable use. Given the heterogeneity of the wheelchair athletes, the first benefit would be to compare current performance to previous measurements, to track training status. Furthermore, interventions in training programme or wheelchair configuration could be evaluated. Once the method is widely used and anonymized performance data is collected, more reference data of

peer athletes becomes available, with increasing level of detail and better peer matching (sport, sex competition level and class) with expansion of the dataset.

As a first step to support the athlete and wheelchair expert in optimizing wheelchair configuration, the effect of several wheelchair settings on wheelchair mobility performance was investigated. The insights based on this study could be used to configure the wheelchair in a way that suits the individual performance target. First pointers regarding the effect of weight, weight distribution, grip and seat height were presented. Those pointers could be used to roughly configure the wheelchair setting, where individual measurements could be applied to attain the best configuration for performance.

The measurements during match and field test (chapter 6) revealed the discrepancy between match and maximal performance, which is of importance to the individual athlete to shape training targets and load, while on sports level it is valuable information to evaluate the sports rules and regulations. Based on this insight, it seems viable to reduce the number of classes in wheelchair basketball, but moreover it stipulates the need for objective performance measurements in setting up classification guidelines. The technological opportunities enable large scale performance data collection, allowing for big data analysis approaches, to identify all confounding factors. Based on such approaches, more substantiated guidelines could be developed, amplifying the fairness of the game.

#### Societal relevance and future perspectives

The transfer from fundamental to applied science is made, the transition from lab to court enabled, unfolding a whole new area of applications and research projects. The new method can be applied to describe wheelchair mobility performance across sports in a more quantitative manner, allowing for better sports referral in the rehabilitation process based on the rehabilitant capacities, but also supporting the (sport) wheelchair fitting process by improving quality and efficiency. But rather than a finalized product, the method developed is the onset of a new era in performance measurement.

Further development of the method by incorporating indoor tracking data, showed much potential and the added value of using inertial sensors. This solution allows for even more sports specific analysis, showing the wheelchair mobility performance needs across court, and also enabling the investigation of team tactics. Another way to extend the wheelchair mobility performance monitor, is not to add sensor concepts, but unwinding the data potential of the inertial sensors, by calculating more athlete specific outcomes. In chapter 10 the possibilities were shown to reliably extract push characteristics in a straight sprint, but once more data are gathered, this type of algorithm development can also be employed for more demanding circumstances or more complex outcomes (e.g. exerted power). Extending the WMPM with more outcomes related to athlete activity patterns, could also be a very powerful tool in setting up evidence based guidelines for classification. In wheelchair basketball a functional classification (match observation based) is used, whereas in wheelchair rugby isolated

functional tests are employed. If wheelchair mobility performance differences in actual match play could be explained by differences in activity pattern due to impairment level, that would be a breakthrough in the ongoing classification discussion. So, the developed method and future extensions could be enforced to further professionalize wheelchair sports, but even wheelchair use in general.

To engage more wheeled sports participation, professional scientific based support is required at all competition levels. At elite level, expertise and application of scientific knowledge is needed to enhance performance, so elite level sports show professionalism and inspire recreational athletes and people in the rehabilitation process with their performance. At recreational level, optimization of available means could be achieved, by efficient selections and configuration of sports wheelchairs and avoiding overuse injuries. A well configured wheelchair and directed advice will enhance sports fun, reducing the risk of early dropping out. Finally, at rehabilitation level, sport participation could be extended with support in selection of the most appropriate sport (Jaarsma, Dijkstra, Geertzen, & Dekker, 2014) and an efficient (sports)wheelchair configuration process, based on evidence-based guidelines. Support at all these levels is important, since it is crucial to lower the barriers for sports participation, to make it accessible for everyone.

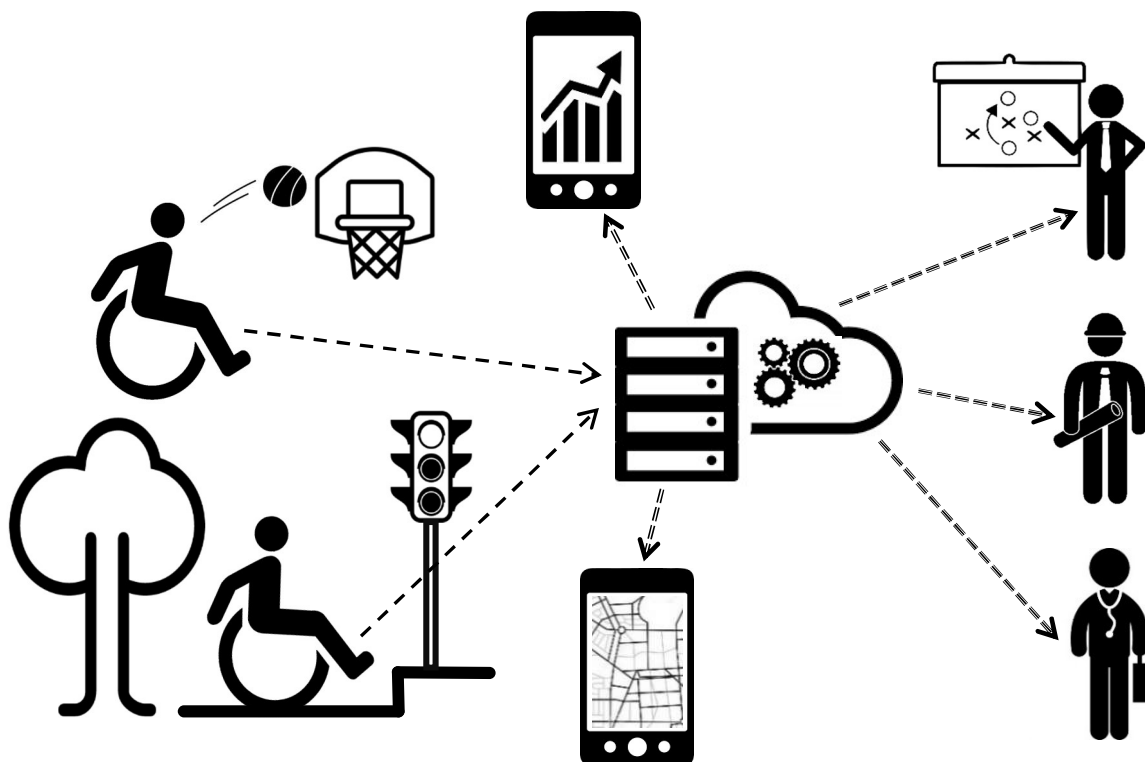


Figure 11.1: Schematic overview of wheelchair tracking, data transfer, cloud analysis, individual output display and possible database use (athletes, coaches, public planners, therapists)

Although this thesis focused on wheelchair sports, the technology used is also applicable for daily wheelchair users. The rapidly increasing use of inertial sensors in the “Internet of Things” (IoT) domain, enables low cost opportunities for developing instrumented wheelchairs. (Sports-)wheelchairs could be fitted with IoT sensors that stream their data to the cloud for further analysis. Individual results could be fed back to the interactive dashboard of the user, whereas anonymised data could be stored to gather sports or daily use wheelchair performance data (Figure 11.1). Such a method for self-tracking of (sports) wheelchair users should address outcomes that are critical for wheelchair use in daily life or sport specific use. By using data science approaches, those big datasets could be used to extract relationships and insights that would never be discovered in conventional wheelchair research approaches. In that sense it could be enforced for accessibility mapping in the public domain or form the bases for evidence-based classification guidelines in Paralympic sports.

#### Round-up

Without compromising towards the scientific level, there was a constant quest to shape the research in such a way that it directly contributed to sports practice. Indeed, research outcomes and methods developed were adopted by those involved in wheelchair basketball, followed by athletes, coaches and sports federations across wheelchair sports, but the tools developed are not yet functional without some technical support. The contribution of a scientist still seems indispensable for the measurement of wheelchair mobility performance, the explanation of WMP plots and guidance on wheelchair configuration. Nevertheless, the empowerment is triggered and barriers for sports practice application notably lowered. It will be a matter of time before wheelchair athletes cannot imagine how to train or play without having regular feedback about their wheelchair mobility performance. It will be a matter of time before wheelchair experts will not configure an athlete’s chair without having a look at the mobility performance plots of the last few months. It will be a matter of time before the International Paralympic Committee will use large mobility performance data sets to review their guidelines on classification. It will be a matter of time before rehabilitation specialists will use wheelchair mobility performance data to guide their rehabilitants towards the best fitting sport. It will be a matter of time before large scale (sports)wheelchair use data will be employed in big data approaches, to come up accessibility mapping and shoulder overload risk models. It will hopefully be a matter of time, before the **Wheelchair Mobility Performance Monitor** helps us to unravel all interactions between *athlete*, *wheelchair* and *sport*.

Using inertial sensors, we move out of the lab, onto the court and beyond. Feel free to join the endeavour to empower wheelchair users in sports and daily live by providing them tools and knowledge to make well considered decisions.





## Publications and outreach

## Publications and outreach

### Full articles for dissertation

#### Article 1 (chapter 2)

Slikke, van der R. M. A., Berger, M. A. M., Bregman, D. J. J., Lagerberg, A. H., & Veeger, H. E. J. (2015). Opportunities for measuring wheelchair kinematics in match settings; reliability of a three-inertial sensor configuration. *Journal of Biomechanics*, 48(12), 3398-3405.

#### Article 2 (chapter 3)

Van der Slikke, R. M. A., Berger, M. A. M., Bregman, D. J. J., & Veeger, H. E. J. (2015). Wheel skid correction is a prerequisite to reliably measure wheelchair sports kinematics based on inertial sensors. *Procedia Engineering*, 112, 207-212.

#### Article 3 (chapter 4)

Slikke, van der, R. M. A., Berger, M. A. M., Bregman, D. J. J., & Veeger, H. E. J. (2016). From big data to rich data: The key features of athlete wheelchair mobility performance. *Journal of Biomechanics*, 49(14), 3340-3346.

#### Article 4 (chapter 5)

de Witte, A. M., Hoozemans, M. J., Berger, M. A., van der Slikke, R. M., van der Woude, L. H., & Veeger, D. (2017). Development, construct validity and test-retest reliability of a field-based wheelchair mobility performance test for wheelchair basketball. *Journal of Sports Sciences*, 1-10.

#### Article 5 (chapter 6)

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#### Article 6 (chapter 7)

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#### Article 8 (chapter 9)

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## Outreach

### Radio

- NPO Radio 1, website: <http://www.nporadio1.nl/nieuws-en-co/onderwerpen/372880-de-ideale-rolstoel-voor-een-paralympische-basketballer> 1 september 2016 17.50 uur
- Radio Stad Delft: <http://www.radiodelft.nl/view-submission/1671>

### TV

- BBC Arabia, 4 Tech:  
<https://m.youtube.com/watch?feature=youtu.be&t=902&v=B74tcorsfU>

### Popular scientific journals

- Annemarie de Witte, Rienk van der Slikke & Monique Berger (2016). Vernieuwing op wielrijes, EOS maandblad voor wetenschap, nr. 9, september 2016  
<http://eoswetenschap.eu/artikel/vernieuwing-op-wielrijes>
- Annemarie de Witte, Rienk van der Slikke & Monique Berger (2015). 'Op weg naar de perfecte sportrolstoel en naar goud in Rio?' *Sportgericht*, 2015, 69 (6), 6-10
- Annemarie de Witte, Rienk van der Slikke, Marco Hoozemans, Monique Berger, Daan Bregman, DirkJan Veeger & Luc van der Woude (2016). De perfecte sportrolstoel in rolstoelbasketbal; op zoek naar de optimale afstemming van rolstoel en atleet. *Human Factors*, 41(3), 27-31

### Paper & digital media

- <https://www.nd.nl/nieuws/nederland/draaicirkels-meten-voor-de-perfecte-sportrolstoel.2501120.lynkx>
- <http://www.ad.nl/delft/onderzoekers-tu-willen-sportstoel-verbeteren~a8de6181/>
- <http://www.omroepwest.nl/nieuws/3348298/Onderzoekers-TU-Delft-werken-aan-perfecte-sportrolstoel>
- <http://www.tudelft.nl/nl/actueel/laatste-nieuws/artikel/detail/tu-delft-meet-bewegingen-rolstoeltenissers-tijdens-abn-amro-world-wheelchair-tennis-tournament/>
- <http://www.supportmagazine.nl/tu-delft-meet-bewegingen-rolstoeltenissers-tijdens-wereldkampioenschap/>
- <http://www.drimble.nl/regio/zuid-holland/delft/41554903/tu-delft-meet-bewegingen-rolstoeltenissers.html>
- <http://www.metronieuws.nl/nieuws/rotterdam/2017/02/onderzoek-voor-perfecte-sportrolstoel-tijdens-wwtt>
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- <http://delft.nieuws.nl/nieuws/5671/tu-delft-meet-bewegingen-rolstoeltenissers-tijdens-abn-amro-world-wheelchair-tennis-tournament/>

About the author  
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Dankwoord

” Life is funny, but not ha ha funny.”

- Mark Oliver Everett, Eels -

### About the author

Rienk van der Slikke was the fourth child of Els van der Slikke-Nijkamp & Jan van der Slikke, born September 22<sup>nd</sup> 1972 in Scheveningen. From early childhood Rienk was always interested in applied technology, often taking equipment apart (not always for the good). Given the constant struggle with grammar and foreign languages, Rienk started with the MAVO after primary school. After four years, Rienk could finally bend his educational path towards technology, starting with the Leidse Instrumentmakersschool (applied precision engineering) in 1988. In 1993 he moved away from hard-core technology and started a bachelor course on “Human Kinetic Technology” (Bewegingstechnologie) in The Hague. This focus on the application of technology to aid human performance is still his main professional interest. In 1997 he received his bachelor degree and started working with McRoberts, a company for ambulatory monitoring equipment. A year later, Rienk also started as a part-time lecturer at Bewegingstechnologie, teaching about motion analysis systems. End 2006, Rienk started as team leader of Bewegingstechnologie, a function he carried out until the commence of his PhD in 2013. Next to his position at Bewegingstechnologie Rienk started a master Human Movement Sciences at the VU university, which he finished in 2014 with distinction.



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Performance in wheelchair court sports is to a large extent determined by the wheelchair mobility performance, the performance measure for the wheelchair-athlete combination. So far, wheelchair mobility performance is mostly utilized as concept, rather than a well quantified measure. However, in order to gain insight in the interaction between *athlete*, *wheelchair* and *sport*, it should be an objective and well quantified outcome that is easily measured. An inertial sensor-based “Wheelchair Mobility Performance Monitor” (WMPM) was developed that met the demands of objective quantification of mobility performance in an easy to use manner. This WMPM is believed to be a valuable tool for wheelchair court sports practice and research. All research done with the WMPM showcases its opportunities and commenced the unravelling of the complex interactions between athlete, wheelchair and sport. It will be a matter of time before the use of the WMPM will be common practice in wheelchair sports and sports research.

