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

van der Slikke, Rienk; Berger, MAM; Bregman, DJJ; Veeger, DirkJan

DOI
10.1016/j.jbiomech.2016.08.022

Publication date
2016

Document Version
Accepted author manuscript

Published in
Journal of Biomechanics

Original article

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

R.M.A van der Slikke[a,b,*], M.A.M. Berger[a], D.J.J. Bregman[b], H.E.J. Veeger[b,c]

[a] Human Kinetic Technology, The Hague University of Applied Sciences, Johanna Westerdijkplein 75, 2521EN The Hague,The Netherlands

[b] Department of Biomechanical Engineering, Delft University of Technology, The Netherlands

[c] Research Institute MOVE, VU, Amsterdam, The Netherlands

Abstract: 265 words

Manuscript: 2765 words

Appendix: 793 words

* Corresponding author at: Human Kinetic Technology, The Hague University of Applied Sciences, Johanna Westerdijkplein 75, 2521EN, The Hague, The Netherlands.
Tel. þ+31704458704.
E-mail address: r.m.a.vanderslikke@hhs.nl (R.M.A vanderSlikke).

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 et al., 2012). Game performance is an overall measure and defined as the true quality of an athlete's contribution to the game (Byrnes et al., 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). Sporner et al. (2009) used a miniature data logger to collect match data of both wheelchair rugby and basketball athletes and claimed 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., 2015a).

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, 2015a) 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., 2015b; 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 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 1

Inertial Measurement Units

The athlete’s wheelchair was equipped with three IMUs (X-IO technologies, Figure 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 1

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. (2015a). Furthermore, a skid correction algorithm was applied to reduce the effect of single or concurrent wheel skidding (van der Slikke et al., 2015b).

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 ^{0} /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 – 2m/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 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 1).

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 2). For subsequent analysis, these six components were used. Table 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 2

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 3, while Figure 4 shows the wheelchair mobility performance if split by competition level.

Figure 3 & 4

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 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 3).

Table 3

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 difference 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 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 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 5

GLMs showed classification as a significant factor in wheelchair performance, but without designating which athletes (classification groups) perform best. Figure 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; Sporner 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., 2015a). Next to this 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). 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 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.

Conflict of interest statement

None.

Acknowledgements

The authors would like to thank Marco Hoozemans (VU) for critical reading and statistical support. This research is funded by the Taskforce for Applied Research (part of Netherlands Organization for Scientific Research) as described in application PRO-4-29.

References

Bloxham, L. A., Bell, G. J., Bhambhani, Y., & Steadward, R. D. (2001). Time motion analysis and physiological profile of Canadian world cup wheelchair basketball players. *Sports Medicine, Training and Rehabilitation*, *10*(3), 183-198.

Byrnes, D., & Hedrick, B. (1994). Comprehensive basketball grading system. *Wheelchair Basketball. Washington, DC: Paralyzed Veterans of America*.

de Witte, A. M., Hoozemans, M. J., Berger, M. A., van der Woude, L. H., & Veeger, D. (2015). Do field position and playing standard influence athlete performance in wheelchair basketball? *Journal of sports sciences*, 1-10.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. Sage.

Fuss, F. K. (2012). Speed measurements in wheelchair sports–theory and application. *Sports Technology*, *5*(1-2), 29-42.

Fuss, F. K., Subic, A., & Chua, J. J. (2012). Analysis of wheelchair rugby accelerations with fractal dimensions. *Procedia Engineering*, *34*, 439-442.

Mason, B., Van Der Woude, L., Lenton, J. P., & Goosey-Tolfrey, V. (2012). The effect of wheel size on mobility performance in wheelchair athletes. *International journal of sports medicine*, *33*(10), 807-812.

Mason, B. S., van der Woude, L. H., & Goosey-Tolfrey, V. L. (2013). The ergonomics of wheelchair configuration for optimal performance in the wheelchair court sports. *Sports Medicine*, *43*(1), 23-38.

Pansiot, J., Zhang, Z., Lo, B., & Yang, G. Z. (2011). WISDOM: wheelchair inertial sensors for displacement and orientation monitoring. *Measurement Science and Technology*, *22*(10), 105801.

Rhodes, J. M., Mason, B. S., Perrat, B., Smith, M. J., Malone, L. A., & Goosey-Tolfrey, V. L. (2015a). Activity profiles of elite wheelchair rugby players during competition. *International journal of sports physiology and performance*, *10*(3), 318-324.

Rhodes, J. M., Mason, B. S., Malone, L. A., & Goosey-Tolfrey, V. L. (2015b). Effect of team rank and player classification on activity profiles of elite wheelchair rugby players. *Journal of sports sciences*, *33*(19), 2070-2078.

Sarro, K. J., Misuta, M. S., Burkett, B., Malone, L. A., & Barros, R. M. (2010). Tracking of wheelchair rugby players in the 2008 Demolition Derby final.*Journal of sports sciences*, *28*(2), 193-200.

Sporner, M. L., Grindle, G. G., Kelleher, A., Teodorski, E. E., Cooper, R., & Cooper, R. A. (2009). Quantification of activity during wheelchair basketball and rugby at the National Veterans Wheelchair Games: A pilot study. *Prosthetics and orthotics international*, *33*(3), 210-217.

Usma-Alvarez, C. C., Chua, J. J. C., Fuss, F. K., Subic, A., & Burton, M. (2010). Advanced performance analysis of the Illinois agility test based on the tangential velocity and turning radius in wheelchair rugby athletes. *Sports Technology*, *3*(3), 204-214.

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

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

Appendix A

Table 4

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 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 60º 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 most pure 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 5

Appendix C

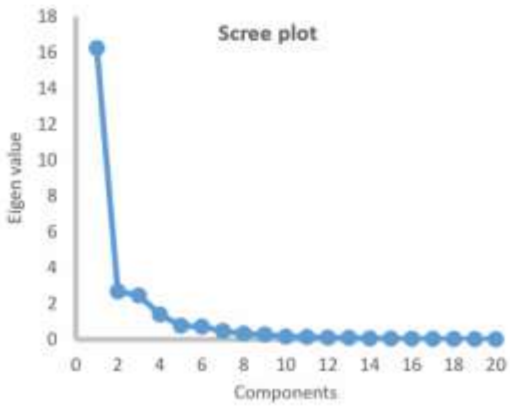
Outcome selection

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 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.

Figures

Figure 1. Measurement setup, with IMUs on wheels and frame and measurements during a match. (Photograph by www.frankvanhollebeke.be).



Component	E.V.	Variance %	Cumulative %
1	16.24	62.47	62.47
2	2.68	10.31	72.78
3	2.45	9.42	82.21
4	1.39	5.35	87.55
5	0.76	2.93	90.48
6	0.71	2.73	93.21
7	0.47	1.82	95.03
8	0.32	1.25	96.28
9	0.27	1.04	97.32
10	0.15	0.58	97.90

Figure 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.

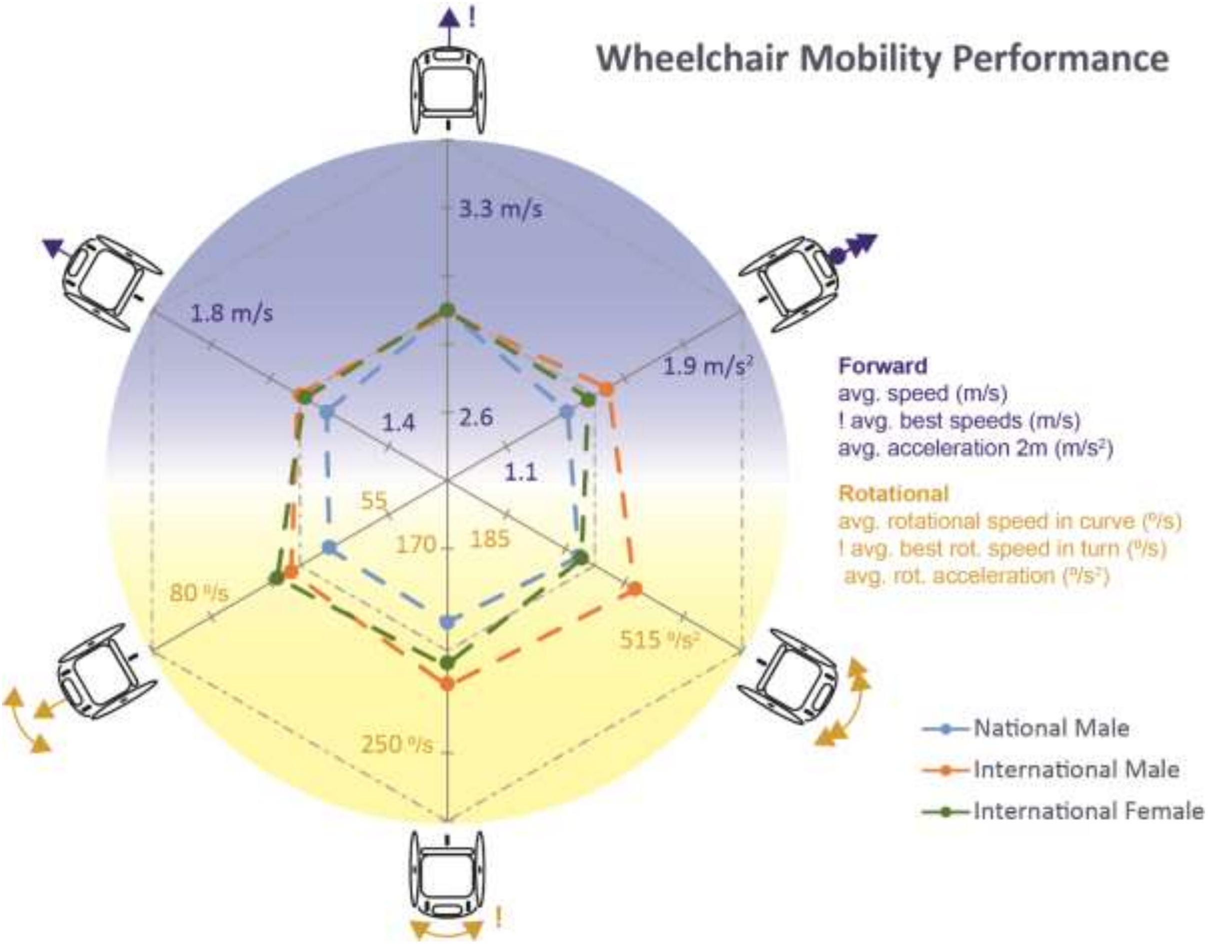
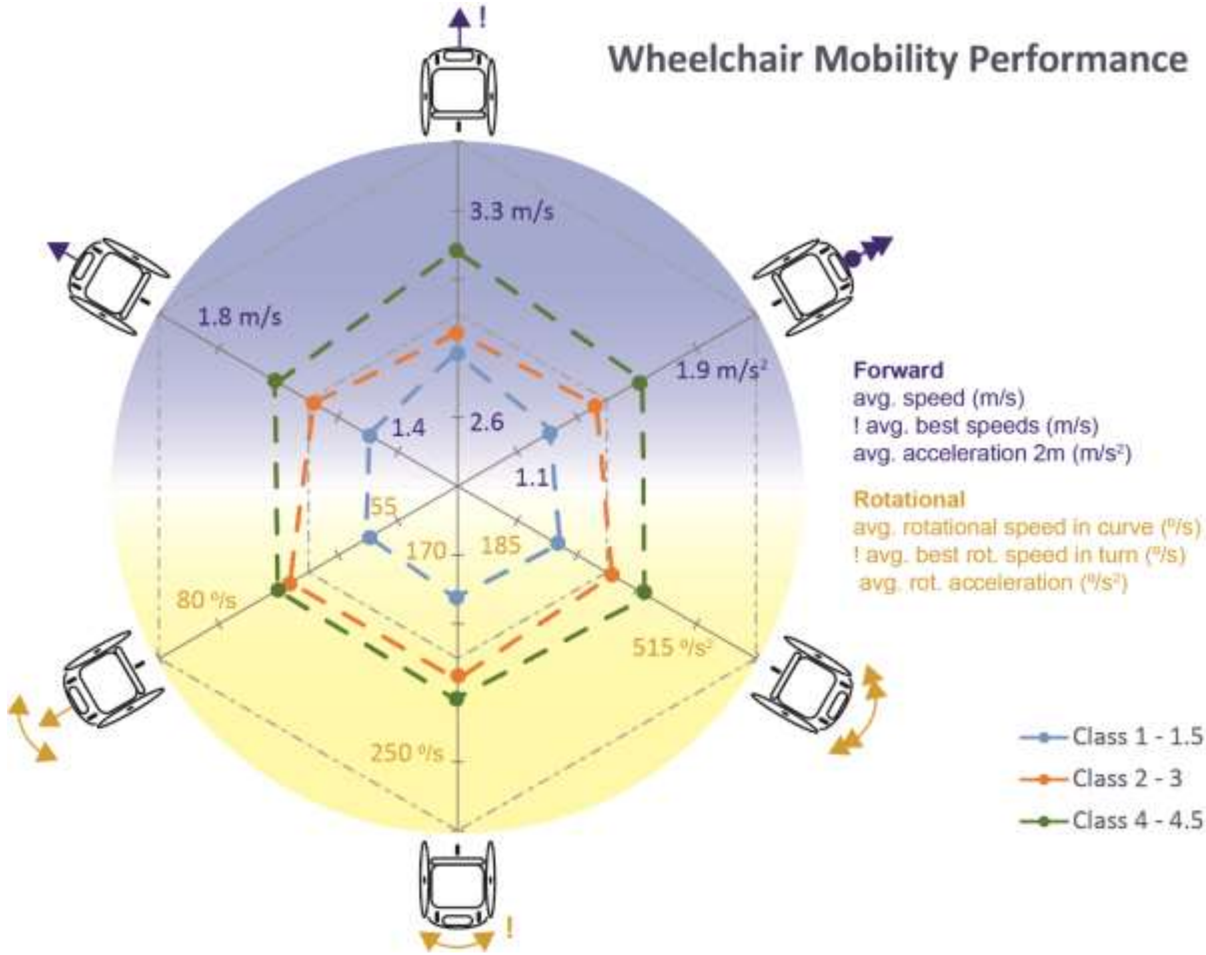


Figure 3. Wheelchair mobility performance plot for three classification groups. The low classified athletes (class 1 – 1.5) perform below average on all six kinematic outcomes. The high classified athletes (class 4 – 4.5) perform best on all outcomes. The middle classified athletes (class 2-3) perform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



389

390 Figure 4. Wheelchair mobility performance plot for three competition level groups. National level athletes perform
391 below average on all aspects, although best forward speed (top) is similar for all groups. International male
392 athletes perform best on all kinematic outcomes, except average rotational speed in a curve, in which
393 international females perform best. In all kinematic outcomes except average rotational acceleration, female
394 internationals perform close to their male couterparts.

395

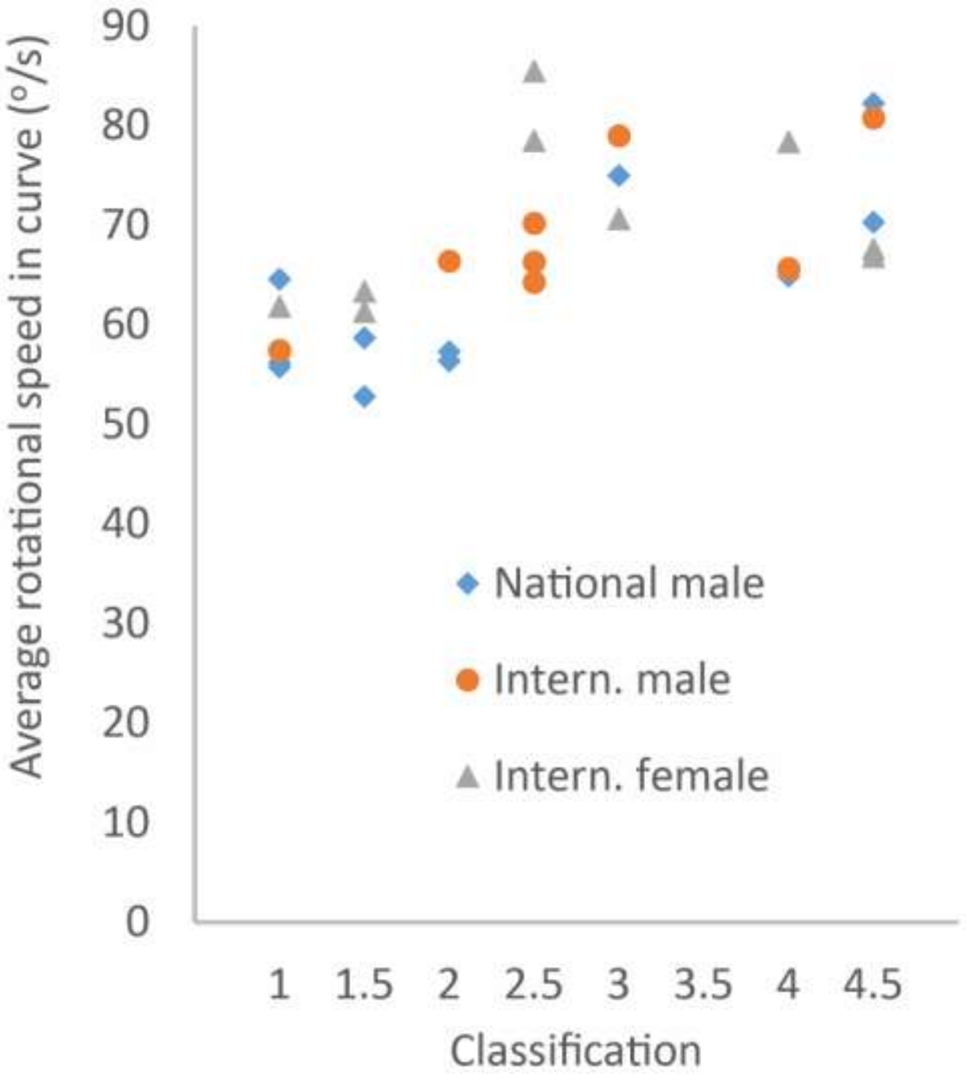


Figure 5. Distribution of average rotational speed in a curve (forward speed > 1.5m/s) per classification, grouped by competition level. The deviating scores (particularly for class 2.5) of the international females clarifies the interactional effect found between classification and competition level, since it disturbs the variance per classification used in the GLM.

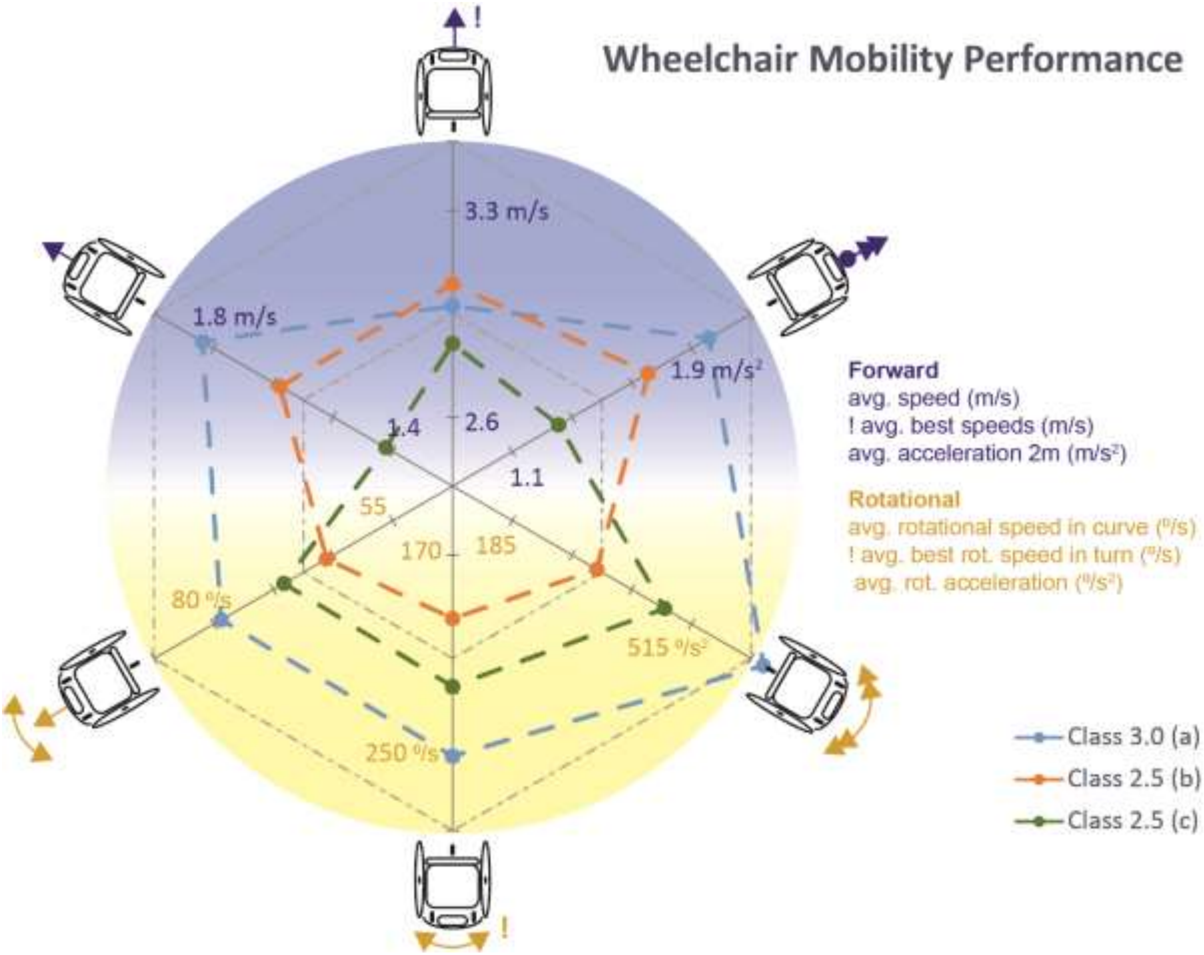


Figure 6. Typical example of the wheelchair mobility performance plot for three individual similar classified international male athletes. The class 3 athlete (a) was very skilled and has a high above knee amputation, so a positive power to weight ratio and low moment of inertia, resulting in high (rotational) 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).

Tables

Table 1. The distribution of classification and age (years) per competition level group.

Level group		***Mean***	***SD***	**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							
Total				**5**	**5**	**5**	**3**	**3**	**5**	**4**

Table 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** 1	**2**	**3**	**4**	**5**	**6**	**Selection per component**
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							

Table 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 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	Compo-nent	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

Table 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 center axle (cm)	Center axle to caster (cm)	Center axle to footplate (cm)	Between wheels (cm)	Between rims (cm)	Track width (cm)	Pivot centers (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

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