

## 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](https://doi.org/10.1016/j.jbiomech.2016.08.022)

#### Publication date

2016

#### Document Version

Accepted author manuscript

#### Published in

Journal of Biomechanics

#### Citation (APA)

van der Slikke, R., Berger, MAM., Bregman, DJJ., & Veeger, D. (2016). From big data to rich data: The key features of athlete wheelchair mobility performance. *Journal of Biomechanics*, 49(14), 3340-3346. <https://doi.org/10.1016/j.jbiomech.2016.08.022>

#### Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

#### Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

#### Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26

Original article

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

R.M.A van der Slikke<sup>a,b,\*</sup>, M.A.M. Berger<sup>a</sup>, D.J.J. Bregman<sup>b</sup>, H.E.J. Veeger<sup>b,c</sup>

<sup>a</sup> Human Kinetic Technology, The Hague University of Applied Sciences,  
Johanna Westerdijkplein 75, 2521EN The Hague, The Netherlands

<sup>b</sup> Department of Biomechanical Engineering, Delft University of Technology, The Netherlands

<sup>c</sup> 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. p+31704458704.  
E-mail address: r.m.a.vanderslikke@hhs.nl (R.M.A vanderSlikke).

## 27 Abstract

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

36 The wheelchair kinematics of 29 (inter-)national level athletes were measured during a match using  
37 three inertial sensors mounted on the wheelchair. Principal component analysis was used to reduce  
38 22 kinematic outcomes to a set of six outcomes regarding linear and rotational movement; speed and  
39 acceleration; average and best performance. In addition, it was explored whether groups of athletes  
40 with known performance differences based on their impairment classification also differed with  
41 respect to these key outcomes using univariate general linear models. For all six key outcomes  
42 classification showed to be a significant factor ( $p < 0.05$ ).

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

## 49 Introduction

50 Since wheelchair basketball has reached an increased level of professionalism, there is a need to  
51 optimize all factors contributing to team performance, like team interplay and individual athlete  
52 performance. The athlete's performance in turn can be sub-divided in physical performance, mobility  
53 performance and game performance. Physical performance only concerns the athlete (Bloxham et al.,  
54 2001), whereas mobility performance is the measure for the combined wheelchair-athlete combination  
55 (Mason et al., 2013). Therefore, although mobility performance is established by athlete exertion, it is

56 often expressed in terms of wheelchair kinematics (Mason et al., 2012). Game performance is an  
57 overall measure and defined as the true quality of an athlete's contribution to the game (Byrnes et al.,  
58 1994). The present study investigated ways to improve quantification and measurement of  
59 **wheelchair mobility performance characteristics**, to enable evaluation of interventions aiming at  
60 optimizing wheelchair-athlete interaction.

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

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

81 The aim of this study was to compose an easy to interpret display of key features best representing  
82 wheelchair mobility performance. Three subsequent steps were undertaken to meet that aim: 1)  
83 reduction of a large number of kinematic outcomes to a set of key kinematic outcomes; 2) seeking a  
84 way to display key kinematic features in a concise but clear fashion, usable for coach and athlete; 3)  
85 testing if key features discriminate well between athletes of different performance levels. Since

86 mobility performance is known to strongly relate to classification in wheelchair rugby (Rhodes et al.,  
87 2015b; Sarro et al., 2010; Usma-Alvarez et al., 2010), it should do so in wheelchair basketball as well,  
88 since both games use the same classification principle. Given this assumed performance difference  
89 due to classification, the new method was rated accurate if indeed classification appeared to be a  
90 significant factor in measured kinematic outcomes.

## 91 **Methods**

### 92 **Setup & Participants**

93 Wheelchair kinematics of wheelchair basketball athletes were measured during 11 premier division  
94 competition and friendly international level matches. Twenty-nine athletes were measured with twelve  
95 male first division athletes (National NLD), nine female internationals (NLD & GBR) and eight male  
96 internationals (NLD, ISR & AUS). Athlete classification was evenly distributed over these three  
97 competition level groups (Table 1, Appendix A). This study was approved by the ethical committee of  
98 the faculty of Human Movement Sciences: ECB-2014-2. All participants signed an informed consent  
99 after being informed on the aims and procedures of the experiment.

### 100 **Table 1**

### 101 **Inertial Measurement Units**

102 The athlete's wheelchair was equipped with three IMUs (X-IO technologies, Figure 1), one on each  
103 rear wheel axis and one on the rear frame bar. The frame sensor was used for measuring forward  
104 acceleration as well as rotation of the frame in the horizontal plane. The combined signal of wheel  
105 sensor acceleration and gyroscope was used to estimate wheel rotation, which in turn provided frame  
106 displacement given the wheel circumference.

### 107 **Figure 1**

108 Horizontal frame rotation estimates were used to correct the wheel gyroscope signal for wheel  
109 camber angle, as described by Pansiot et al. (2011), Fuss et al. (2012) and van der Slikke et al.  
110 (2015a). Furthermore, a skid correction algorithm was applied to reduce the effect of single or  
111 concurrent wheel skidding (van der Slikke et al., 2015b).

## 112 Analysis

### 113 *Kinematic outcomes*

114 A total of 22 wheelchair kinematic outcomes regarding forward and rotational movement were initially  
115 extracted from the IMU based measurement method. To enable genuine comparison independent of  
116 match time, average kinematic outcomes were calculated for actual movement time ( $>0.1$  m/s) and  
117 rotation time ( $> 10^0$  /s) respectively. For all movements of at least 0.5 seconds, basic kinematic  
118 outcomes were calculated: forward frame displacement, speed, acceleration, rotation in the horizontal  
119 plane, rotational speed and rotational acceleration. Additionally, combined kinematic outcomes were  
120 calculated including rotational kinematic outcomes with minimal forward speed (turn) and rotational  
121 kinematic outcomes while driving (curve). Both turn and curve kinematic outcomes were calculated  
122 with different boundaries for forward speed (FS): “turn”, FS  $-0.5 - 0.5$  m/s; “turn2”, FS  $-1.5 - 1.5$  m/s  
123 ( $1.5$ m/s equals average FS); “curve”, FS  $1 - 2$ m/s and “curve2”,  $1.5+$ m/s. For all (rotational) speed  
124 related kinematic outcomes, also averages of best ( $n=5$ ) performances were calculated (see  
125 Appendix B for a more detailed description of outcomes).

### 126 *Statistics*

127 Principal Component Analysis (PCA) was used to reduce the number of kinematic outcomes to arrive  
128 at independent key factors that describe an athlete’s wheelchair mobility performance. The Kaiser-  
129 Meyer-Olkin test was used to verify if the dataset of 22 outcomes was suitable for PCA (KMO value  
130  $>.5$ ). The PCA was applied with a VariMax rotation to identify components that are not highly  
131 correlated. The point of inflexion in the scree-plot was used to make an initial selection for the number  
132 of retaining components (Field, 2013). The PCA shows how well each of the 22 kinematic outcomes  
133 load ( $-1 < 1$ ) on those retaining components. For each component, one kinematic outcome was  
134 selected, typically the one with the highest loading. In case of a nearly similar loading of several  
135 outcomes on a component, also the second or third outcome could be selected based on conceptual  
136 reasons. Less complex outcomes, easier to interpret for sports application were preferred over more  
137 complex outcomes and a somewhat even distribution between outcomes describing linear or  
138 rotational kinematics was aimed at (see Appendix C for application of this concept to the results).

139 Univariate one-way ANOVA’s (General Linear Models) were used to test whether groups of athletes  
140 with different performance levels (different classification) also differed with respect to the key

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

148

## 149 Results

### 150 Kinematic outcomes

151 Due to high impacts in matches, there was malfunctioning of one of the three sensors in two  
152 measurements. One athlete could be measured in a subsequent match, so only the measurement of  
153 one international male athlete was lost and the kinematic outcomes of 29 athletes were used in the  
154 PCA (Table 1).

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

164 **Table 2**

### 165 Graphical display

166 To support the use of the new set of wheelchair mobility performance outcomes, results were  
167 displayed in a single easy to interpret radar plot with an innate axis for each outcome. The upper and  
168 lower limit per axis is set by the group average plus and minus 2.5 standard deviations. The PCA

169 allowed for an even distribution of kinematic outcomes regarding forward or rotational movement. For  
170 each direction an average speed measure, a best speed measure and average acceleration measure  
171 was selected. The top half of the plot describes forward motion and the lower half rotational kinematic  
172 outcomes, with from left to right: average (rotational) speed, best (rotational) speed and average  
173 acceleration. If grouped by three classification groups, the wheelchair mobility performance plots look  
174 like Figure 3, while Figure 4 shows the wheelchair mobility performance if split by competition level.

175 **Figure 3 & 4**

## 176 Performance and selected kinematic outcomes

177 Once reduced to the six key outcomes, this set of kinematic outcomes was tested for differences in  
178 wheelchair mobility performance between impairment classification levels. For each kinematic  
179 outcome a univariate ANOVA was performed with classification as independent factor. Table 3 shows  
180 that classification is a significant factor ( $p < 0.05$ ) in each GLM after the Holm-Bonferroni correction ( $p$   
181  $< 0.008 - 0.05$ ). To test if the effects for classification hold for all competition levels, two-way  
182 ANOVA's with the interaction of classification and competition level as independent factor was  
183 performed. The effect of classification on average rotational speed in a curve appeared to be  
184 significantly different over competition level groups. The interaction did not show to be significant in  
185 the ANOVA's of the other five outcomes after Holm-Bonferroni correction, although two of them were  
186 borderline significant (Table 3).

187 **Table 3**

## 188 Discussion

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

192 To avoid overly substantial data reduction at this stage, a selection in the principal component  
193 analysis was made based on the second point of inflexion in the scree plot (Figure 2). Future analysis  
194 on enlarged datasets might point at possibilities for more profound data reduction, without significant  
195 information loss. For each of the six PCA components one kinematic outcome was selected. This  
196 selected outcome was not per se the one with the highest loading, but *one* of the *three* outcomes with



197 the highest loadings. This selection criterion made it feasible to select a set of kinematic outcomes  
198 that was nicely distributed, in terms of direction of movement and average or best performance, while  
199 still representing all different PCA components found.

200 The athlete's classification, assumed to be related to mobility performance level, showed to be a  
201 significant factor in univariate GLMs of all selected kinematic outcomes. For one of the key kinematic  
202 outcomes (average rotational speed in a curve) a significant interaction between classification and  
203 competition level appeared. This may imply that classification is not a similar factor in all competition  
204 level groups for this outcome. Graphical display of the results (Figure 5) show that the outcomes of  
205 the female internationals deviate from the national and international males, particularly in the athletes  
206 classified as 2.5. If analysed separately (male/female), classification still appeared to be a significant  
207 factor in GLM models, but then results were drawn from very small data set per group. Future  
208 enlarged datasets should point out if indeed classification has a different effect on average rotational  
209 speed in a curve for female internationals, compared to males.

#### 210 **Figure 5**

211 GLMs showed classification as a significant factor in wheelchair performance, but without designating  
212 which athletes (classification groups) perform best. Figure 3 shows the wheelchair mobility  
213 performance for three classification groups, somewhat equally distributed by competition level. Not  
214 surprisingly and in accordance with findings in wheelchair rugby (Sarro et al., 2010; Sporner et al.,  
215 2009), higher classified athletes achieve higher best and average speeds during match play.  
216 Rotational speeds were higher for higher classified athletes, both in a turn (below average forward  
217 speed) and in a curve (above average speed). Higher classified athletes also showed higher average  
218 acceleration from standstill and higher average rotational acceleration. Similar conclusions were  
219 drawn by Rhodes who reported more high intensity activity in higher classified wheelchair rugby  
220 players (Rhodes et al., 2015a). Next to this more general tendencies of higher classified athletes  
221 being faster and performing at higher intensity (higher average acceleration), the current graph nicely  
222 shows that 2 -3 classified athletes perform in-between low (1 – 1.5) and high (4 -4.5) classified  
223 athletes concerning forward movement, but perform close to the high classified athletes in rotational  
224 movement. Additional measurements should point out if this is a general performance pattern or that it  
225 is partially affected by the slightly higher number of male internationals in this particular group.

226 Differences between competition level groups amply stay within the variance in wheelchair mobility of  
227 athletes with different classifications (Figure 4). Again the new graph not only allows to rate the  
228 performance level in general, but also shows that international level female athletes perform similar to  
229 their male counterparts concerning (rotational) speeds, but at a reduced intensity. So, the wheelchair  
230 mobility graph allows for straightforward, yet detailed comparison of athlete groups.

231 Next to group wise analysis, the wheelchair mobility performance graph also supports individual  
232 athlete comparisons, as can be seen in the example of Figure 6 showing the results of three similarly  
233 classified male international players. To support evaluation of individual training schedules or  
234 wheelchair interventions, the wheelchair mobility performance measurements could be performed on  
235 a regular basis, to display results of consecutive measurements.

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

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

251 The new method to display wheelchair mobility performance is easy to interpret and yet  
252 discriminative. Using this generally applicable and yet detailed quantification of mobility performance  
253 allows for effective evaluation of interventions regarding wheelchair design, changes in wheelchair  
254 settings or changes in athlete training. In that way, it is an important tool to evaluate the effect of any

255 future innovation aiming at improving wheelchair mobility performance, not only in wheelchair  
256 basketball, but also in any wheelchair-based sport. Future research should be directed at finding sport  
257 specific mobility performance profiles, based on the key kinematics of wheelchair mobility  
258 performance.

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

## 262 Conflict of interest statement

263 None.

## 264 Acknowledgements

265 The authors would like to thank Marco Hoozemans (VU) for critical reading and statistical support.

266 This research is funded by the Taskforce for Applied Research (part of Netherlands Organization for  
267 Scientific Research) as described in application PRO-4-29.

## 268 References

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

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

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

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

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

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

282 Mason, B., Van Der Woude, L., Lenton, J. P., & Goosey-Tolfrey, V. (2012). The effect of wheel size  
283 on mobility performance in wheelchair athletes. *International journal of sports medicine*, 33(10), 807-  
284 812.

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

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

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

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

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

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

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

303 Van Der Slikke, R. M. A., Berger, M. A. M., Bregman, D. J. J., Lagerberg, A. H., & Veeger, H. E. J.  
304 (2015a). Opportunities for measuring wheelchair kinematics in match settings; reliability of a three  
305 inertial sensor configuration. *Journal of biomechanics*, 48(12), 3398-3405.

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

309

## 310 Appendix A

311 Table 4

## 312 Appendix B

### 313 Outcomes of wheelchair kinematics

314 The IMU based measurement method for measuring wheelchair kinematics as described by van der  
315 Slikke et al. (2015a) provides information on movement and direction of movement of the wheelchair.  
316 This information is the basis for a wide variety of kinematic outcomes available to outline wheelchair  
317 movement during the measurement. This appendix describes the outcomes (Table 5) and their  
318 structure used.

#### 319 *Forward and rotational movement*

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

327 Rotational movement describes the changes in orientation of the wheelchair in the horizontal plane,  
328 so the (change in) movement direction. In a “turn on the spot” there is only rotation of the wheelchair,  
329 without (significant) forward displacement. Whereas a “curve” is defined as the combination of forward  
330 movement with rotation. Like forward movement rotation could be described by rotation angle,  
331 rotational speed and rotational acceleration. For rotational speed absolute values were taken, so left

332 and right direction rotations were merged, since previous analysis did not show significant differences  
333 between rotational directions.

#### 334 *Thresholds*

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

#### 342 *Average or best*

343 To summarize the complete measurement averages of outcomes were calculated such as average  
344 speed. Like described in the method section, the measurement was also split in discrete sections of  
345 movement (of at least 0.5s) that also provided kinematic outcomes per section. These outcomes were  
346 either averaged (general match performance) or the best 5 outcomes were averaged (best match  
347 performance). For the selected outcomes in PCA, the forward movements of at least 2m occurred on  
348 average 165 (+/- 53) times and the rotational movements 560 (+/- 161) per measurement. So the best  
349 forward speed is 5 out of 165 (on average) and the best turn comprises 5 out of 560 (on average).

350 **Table 5**

## 351 **Appendix C**

### 352 **Outcome selection**

353 Given the aim of this research to provide a useful tool for both scientists and athletes, the selection of  
354 outcomes was not done based on strict PCA conditions alone, but the chosen method allowed for  
355 minimal leeway. This appendix describes the interpretation of the selection concept as described in  
356 the method section. Concept wise the most elegant selection would be a “best” and “average”  
357 outcome of (rotational) speed and (rotational) acceleration, resulting in eight outcomes. Based on the

358 criteria used, only six components were selected. To retain an even distribution between forward and  
359 rotational movement, the “best” or “average” outcome of one magnitude needed to be dropped.

360 Table 2 shows all retained (n=6) components and the loading of each kinematic outcome. The first  
361 component has by far the highest explained variance, so for this selection no compromise was made  
362 and the outcome with the highest loading was selected (best rotational speed in turn2). The loading  
363 (second best) on component 2 and 3 allowed for the selection of average (rotational) acceleration,  
364 which is a very straight forward and stable outcome, representing the intensity of wheelchair  
365 performance. For component 6, only one outcome loaded substantially (best forward speed), so this  
366 one was selected. For component 5, only rotational speeds loaded, so the outcome with the highest  
367 loading was selected (average rotational speed in curve2). To keep an even distribution between  
368 forward and rotational movement, for component 4 the third best outcome was selected (average  
369 forward speed). So in conclusion, in three cases the outcome with the highest loading per component  
370 was selected, in one case (component 2) the second best outcome was chosen but with minimal  
371 difference to the best and finally for two components (2 & 4) conceptual motivations prevailed  
372 somewhat over outcome loading on the component.

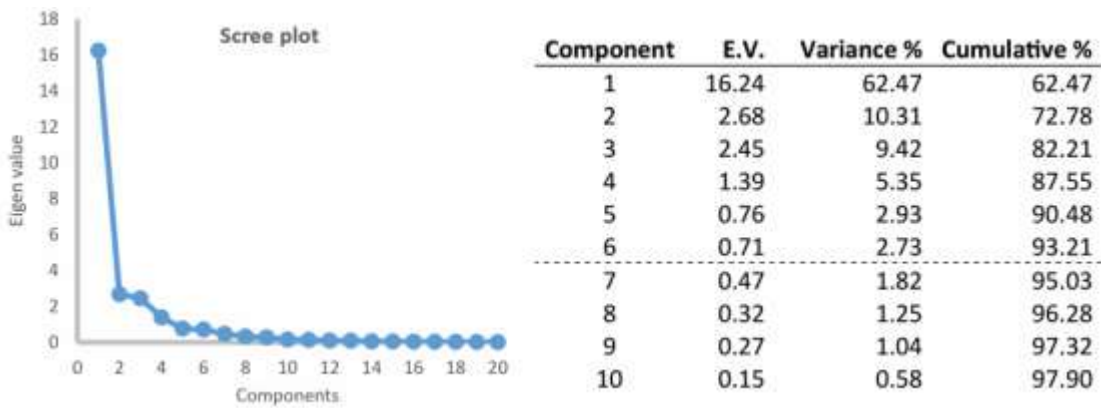
373



375

376 Figure 1. Measurement setup, with IMUs on wheels and frame and measurements during a match. (Photograph  
 377 by [www.frankvanhollebeke.be](http://www.frankvanhollebeke.be)).

378

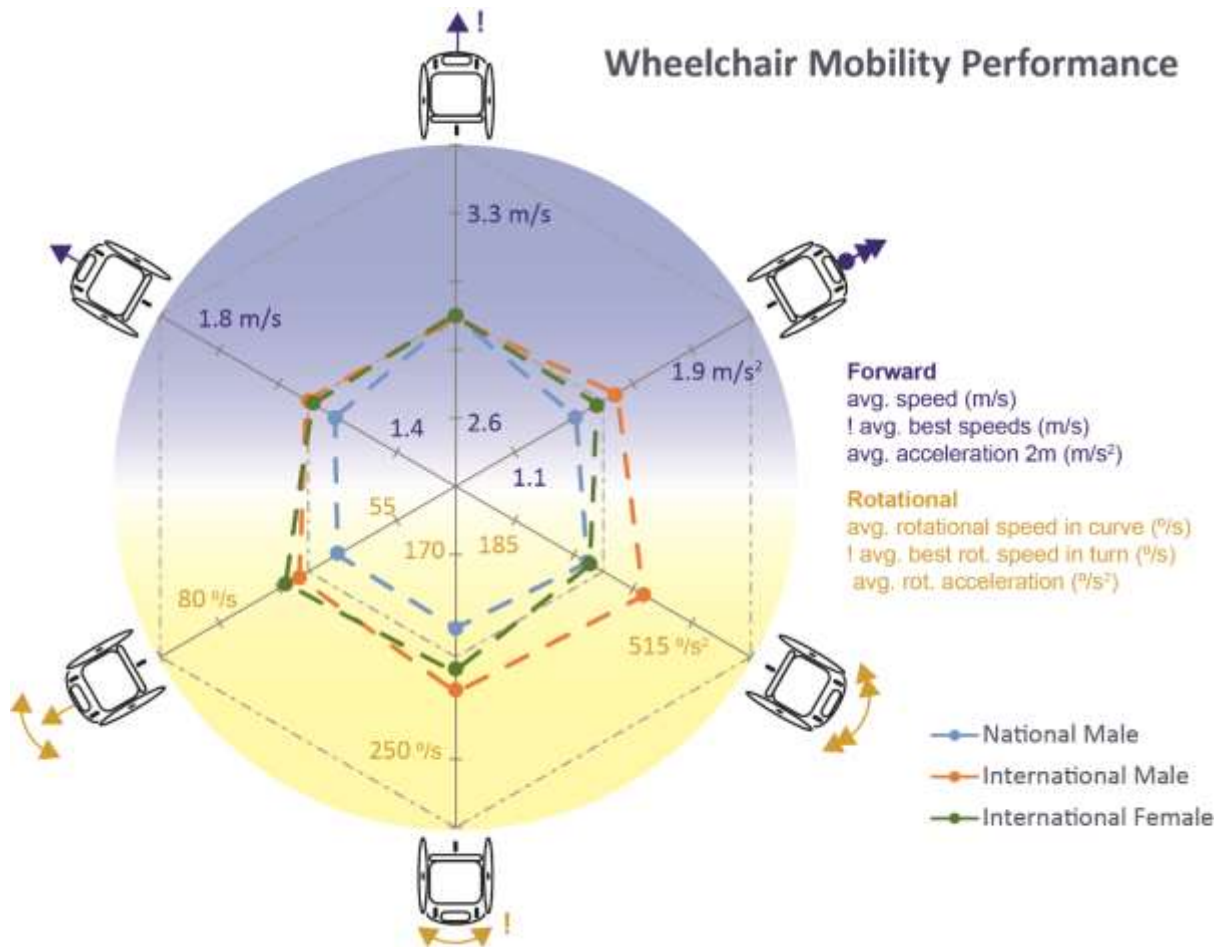


379

380 Figure 2. Scree plot for principal component analysis with the table on the right showing initial Eigen Values  
 381 (E.V.) and explained variance for the first 10 components.

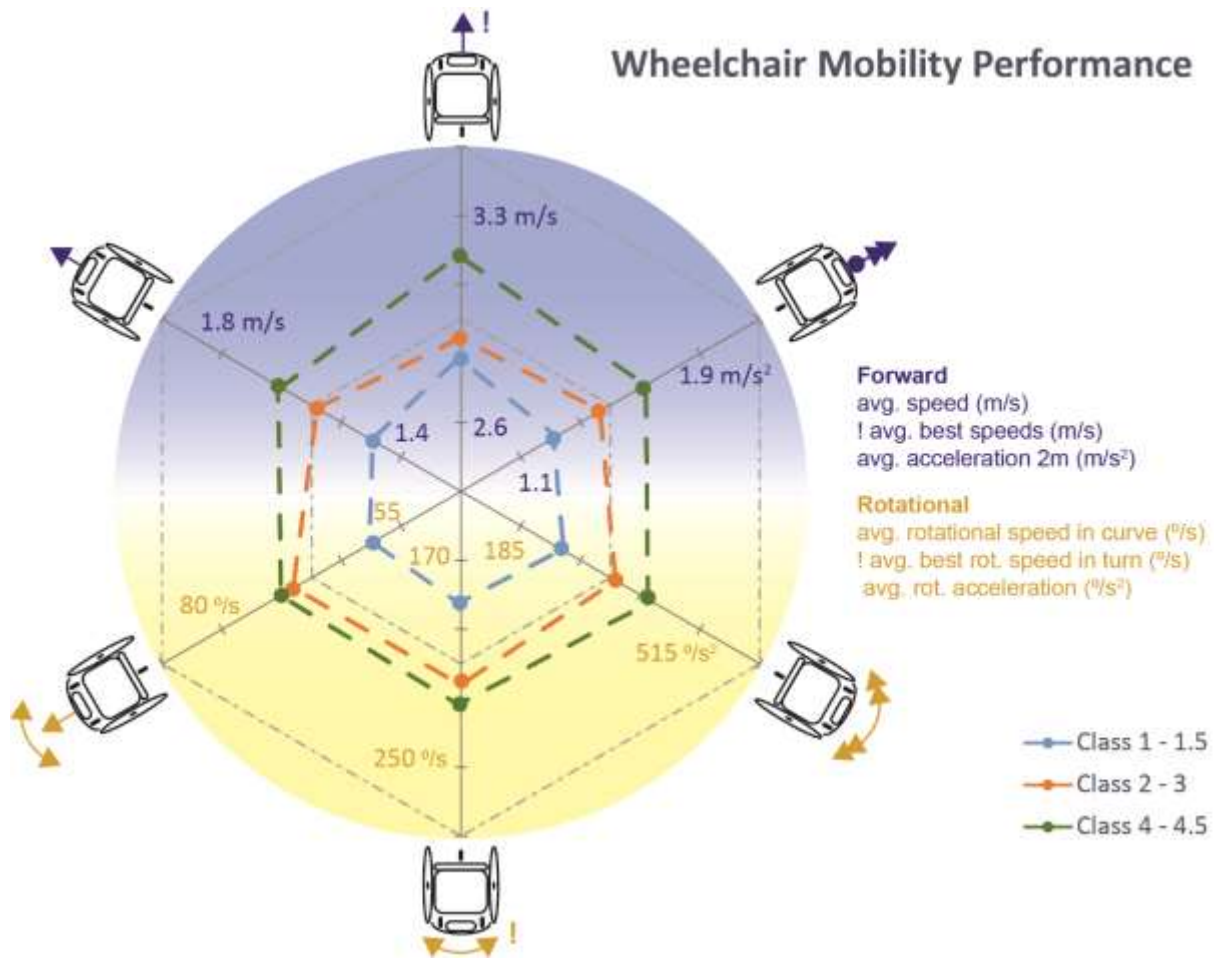
382





383

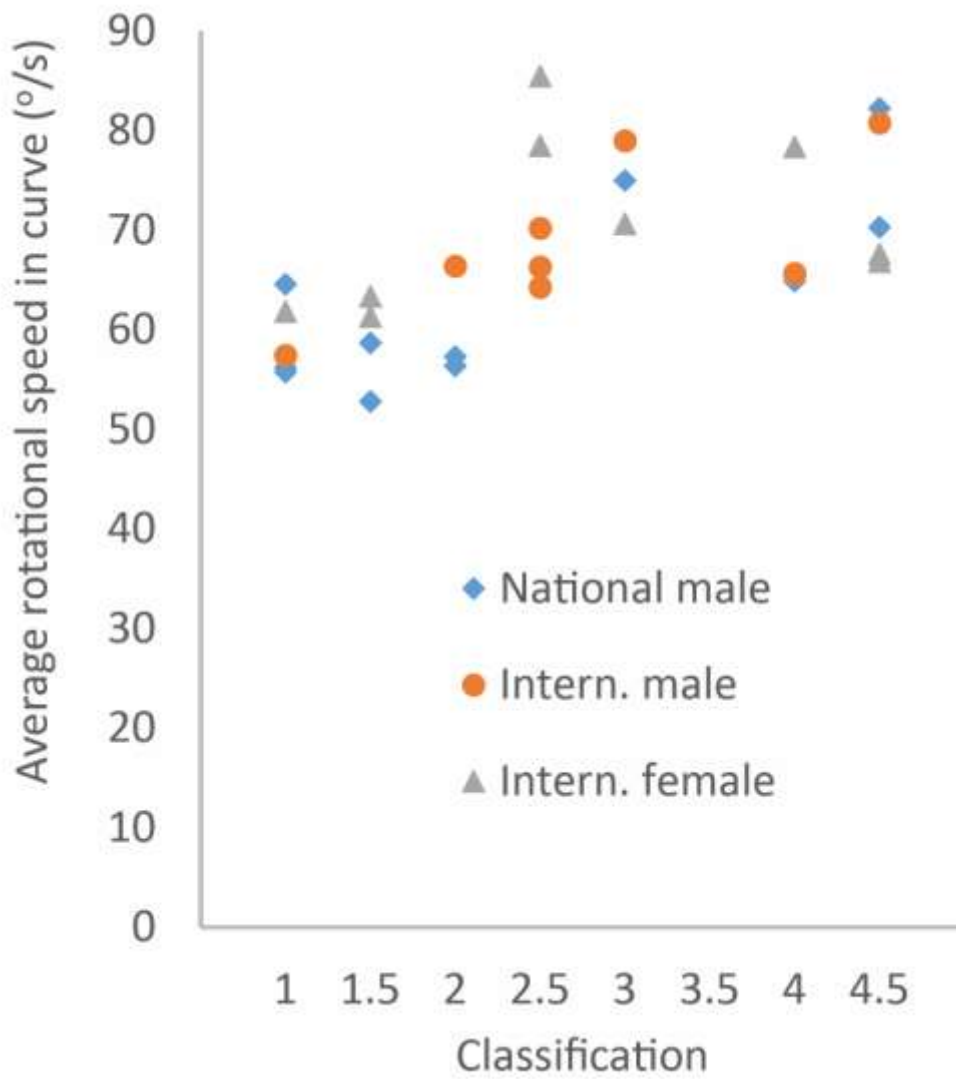
384 Figure 3. Wheelchair mobility performance plot for three classification groups. The low classified athletes (class 1  
 385 – 1.5) perform below average on all six kinematic outcomes. The high classified athletes (class 4 – 4.5) perform  
 386 best on all outcomes. The middle classified athletes (class 2-3) perform close to the low classified athletes  
 387 regarding best forward speed (top), but close to high classified athletes regarding rotational speeds (bottom left  
 388 and bottom).



389

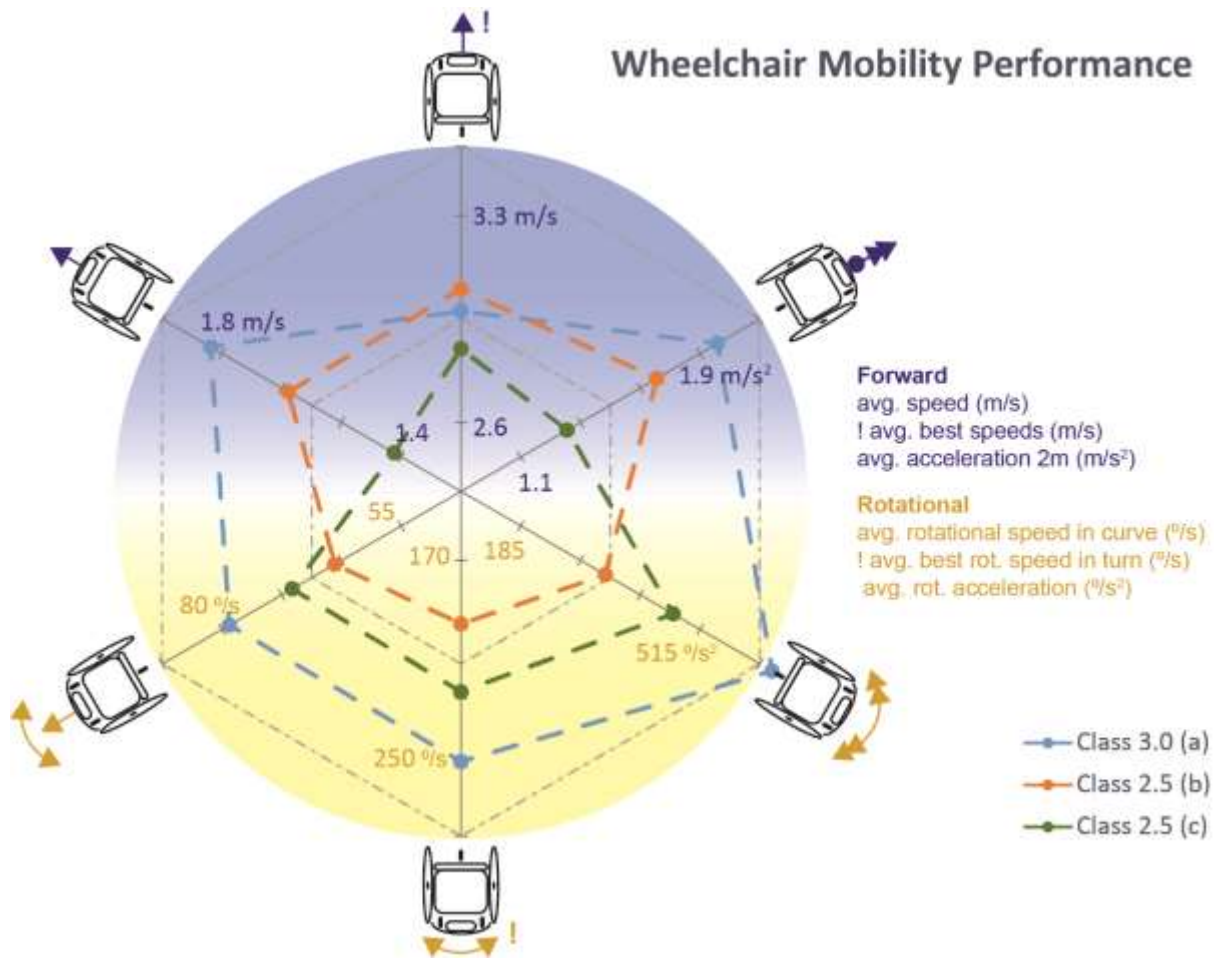
390 Figure 4. Wheelchair mobility performance plot for three competition level groups. National level athletes perform  
 391 below average on all aspects, although best forward speed (top) is similar for all groups. International male  
 392 athletes perform best on all kinematic outcomes, except average 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 counterparts.

395



396

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



401

402 Figure 6. Typical example of the wheelchair mobility performance plot for three individual similar classified  
 403 international male athletes. The class 3 athlete (a) was very skilled and has a high above knee amputation, so a  
 404 positive power to weight ratio and low moment of inertia, resulting in high (rotational) speeds and accelerations.  
 405 The two class 2.5 athletes have different wheelchair settings, with b below average and c above average seat  
 406 height, adjusted to their field role (guard and centre respectively).

407

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

<i>Level group</i>		<i>Mean</i>	<i>SD</i>	<b>Classification</b>						
				<b>1</b>	<b>1.5</b>	<b>2</b>	<b>2.5</b>	<b>3</b>	<b>4</b>	<b>4.5</b>
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>

410

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

<b>Outcome Number</b>	<b>Direction</b>	<b>Order</b>	<b>Type</b>	<b>Avg or Best</b>	<b>Component</b>						<b>Selection per component</b>	
					<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>		
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								

417

418 Table 3. The p value of classification and the interaction of classification with competition level in univariate GLMs  
 419 for each of the selected kinematic outcomes (see Table 2 for abbreviations). \* indicates significant p values  
 420 ( $p < 0.05$ ) 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

421

422

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

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

427

428

429