

## **Effects of moment of inertia on restricted motion swing speed**

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1       **Effects of moment of inertia on restricted motion swing speed**

2       **Abstract**

3       In many sports, the maximum swing speed of a racket, club or bat is a key performance  
4 parameter. Previous research in multiple sports supports the hypothesis of an inverse  
5 association between the swing speed and moment of inertia of an implement. The aim of  
6 this study was to rigorously test and quantify this relationship using a restricted swinging  
7 motion. Eight visually identical rods with a common mass, but variable moment of inertia  
8 were manufactured. Motion capture technology was used to record eight participants'  
9 maximal effort swings with the rods. Strict exclusion criteria were applied to data that did  
10 not adhere to the prescribed movement pattern. The study found that for all participants,  
11 swing speed decreased with respect to moment of inertia according to a power relationship.  
12 However, in contrast to previous studies, the rate of decrease varied from participant to  
13 participant. With further analysis it was found that participants performed more  
14 consistently at the higher end of the moment of inertia range tested. The results support  
15 the inverse association between swing speed and moment of inertia but only for higher  
16 moment of inertia implements.

17       Word Count: 184

18

19       **Key words:** Swing-weight, rods, tennis, motion analysis

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## 22      **Introduction**

23      In sports that involve a swinging motion, one of the most important physical properties of  
24      an implement is the moment of inertia about an axis normal to the primary swing plane  
25      (Cross & Nathan, 2009). Moment of inertia (MOI) is a measure of an object's resistance to  
26      angular acceleration about a given axis and is one of the limiting factors for maximum swing  
27      speed.

28      Participants can be highly sensitive to changes in moment of inertia, especially at an elite  
29      level (Brody, 2000). It has been shown that people are up to ten times more sensitive to  
30      differences of MOI than differences in mass for objects in the range 0.3 to 0.5 kg (Kreifeldt  
31      & Chuang, 1979). Multiple studies suggest that the moment of inertia of an implement has  
32      an inverse association with swing speed, with evidence in Baseball (Koenig, Mitchell,  
33      Hannigan, & Clutter, 2004), Golf (Daish, 1972) and Tennis (Mitchell, Jones, & King, 2000). All  
34      of these studies used at least four implements and found that increasing MOI reduced  
35      swing speed. However, the range in MOI of the tested implements was relatively small and  
36      mass was not kept constant. Smith, Broker and Nathan (2003) undertook similar work in  
37      Softball with ten bats of constant mass and ten bats of constant MOI. They showed that  
38      swing speed has a high dependence upon MOI but little dependence on bat mass. However,  
39      this study also focused on a relatively small range of moment of inertia (0.128 - 0.200 kgm<sup>2</sup>).

40      In previous studies, the participants performed a motion typical to the sport being  
41      considered – skill and experience were important factors in the selection of participants in  
42      these studies. Each participant performs at different levels of consistency and habitually  
43      uses equipment with a specific moment of inertia. Mitchell and co-workers (2000) found

44 that in tennis, individuals performed best with rackets whose MOI (measured 0.1m from  
45 the butt end) closest matched that of their own racket.

46 Cross and Bower (2006) attempted to overcome the potential complicating factors of  
47 participant skill and experience by testing a simple restricted motion. Using a one armed,  
48 overhead motion in the sagittal plane, participants swung six weighted rods with a large  
49 range of mass (0.208 - 0.562 kg) and moment of inertia (0.0103 - 0.1034 kgm<sup>2</sup>). A similar  
50 trend of decreasing swing speed with increasing moment of inertia was found and a  
51 common power law relationship was defined,

$$52 \quad V = \frac{C}{I_o^n} \quad (1)$$

53 where  $V$  is swing speed,  $C$  is a participant constant,  $I_o$  is the moment of inertia and  $n$  is  
54 the gradient of the best fit trend line. The  $n$  value in literature is found to be between 0.25-  
55 0.29 (Daish, 1972; Smith et al., 2003; Cross and Bower, 2006; Nathan, Crisco, Greenwald,  
56 Russel and Smith, 2011) and further work in softball found the value of  $n$  to lie between  
57 0.20-0.25 (Smith & Kensrud, 2014; Smith, Burbank, Kensrud, & Martin, 2012). These studies  
58 have remarkably similar results despite focussing on different sports or movements.  
59 However, in work by Cross and Bower (2006), relationships appear to have been  
60 established using as few as two or three data points. In addition, implement weighting was  
61 not concealed, meaning participants may prepare to perform differently. Furthermore,  
62 there is evidence from a meta-analysis to suggest that this relationship may exist between  
63 swing speed and MOI across a wide range of sports (Schorah, Choppin, & James, 2012).  
64 However, as this work did not involve data collection, more experimental work is required to  
65 confirm this.

66 When swung, an implement's moment of inertia influences the transfer of energy to  
67 another object where there is an impact. For a given swing speed, a higher MOI generally  
68 produces a higher outbound ball speed (Bahill, 2004). However, because a higher MOI  
69 generally results in a lower swing speed, it is likely that this is only true up to a limit.  
70 Therefore, it is likely that the optimal implement moment of inertia for an individual will be  
71 strongly influenced by their skill level or physical strength. For skilled actions, as used in  
72 some of the literature, such as throwing an object or striking an object with a swung  
73 implement, there is also a trade-off between the speed of the action and the accuracy of  
74 the performed task. The optimum point of this speed-accuracy trade-off was found to be at  
75 70% of maximal throwing speed for baseball players (Freeston & Rooney, 2014) but there is  
76 also evidence to suggest that this trade-off only applies when a player is performing with  
77 their dominant side (Sachlikidis & Salter, 2007). The kinematics of a swing is also closely  
78 linked to resulting swing speeds (Joyce, Burnett, Cochrane, & Ball, 2013) and players have  
79 been found to control the variability in their swing to keep the outcome consistent (Tucker,  
80 Anderson, & Kenny, 2013).

81 The aim of this study was to experimentally test the relationship between swing speed  
82 and moment of inertia during a restricted motion with a rigorous protocol and a larger  
83 number of participants than many previous studies. It is hypothesised that the value for  $n$   
84 will be the same for all participants and will lie within the range 0.20-0.29.

## 85 **Methods**

86 This study used a motion capture system to record the speed of weighted rods swung by  
87 participants in a laboratory.

88 *Participants*

89 Once approval was received from the Faculty of Health and Wellbeing Research Ethics  
90 Committee at Sheffield Hallam University, eight participants with a range of statures and  
91 builds were recruited. The group consisted of six males and two females and all participants  
92 were healthy, active individuals with an age of  $25.1 \pm 5.4$  years, mass of  $73.3 \pm 16.5$  kg and  
93 height of  $1.79 \pm 0.27$  m. The participants were all active and with no prior experience of  
94 performing the motion in the study.

95 *Rods*

96 This study used eight, visually identical rods made from 0.0254 m diameter, hollow  
97 aluminium tubing. In order to vary moments of inertia, a solid mass of 0.16 kg was fixed  
98 within each rod at varying locations along the length. Each rod was capped at either end,  
99 had a length of 0.506 m and a total mass of 0.32 kg (including the additional mass).

100 Table 1 shows the length ( $L$ ), mass ( $M$ ), balance point ( $L_{cm}$ ) measured from the butt end  
101 of the rod, and moment of inertia ( $I_{rod}$ ) about a perpendicular axis through the butt end of  
102 the rod, for the 8 rods. The moment of inertia of the rods was calculated using the method  
103 described by Brody (1985), taken about an axis through the butt end, perpendicular to the  
104 rod's centreline. Moment of inertia values ranged from 0.0113 to 0.0495  $\text{kgm}^2$  (Table 1),  
105 representing the moment of inertia of a typical badminton racket to a typical tennis racket.  
106 The moment of inertia measurements were estimated to be subject to error less than 1%,  
107 which was deemed acceptable.

108 Figure 1 shows the bespoke attachment used to fix the rods to the back of the  
109 participant's wrist. The attachment for the rods had a mass of 0.16 kg, positioned at the

110 base of the rod and the wrist guard had a mass of 0.076 kg. To account for the effect of this  
111 attachment, the rod's moment of inertia was re-calculated about the participant's elbow,  
112 and included the mass of the attachment and wrist guard,  $I_{Elbow}$ .

113 The distance from a participant's elbow to wrist was calculated from motion capture data.  
114 This method provided a more accurate description of each rod's resistance to angular  
115 acceleration, but it also reduced the range in moment of inertia values. Nonetheless, the  
116 experimental range still exceeded moment of inertia values typically found in tennis.

117 The rods were labelled 1 to 8 in a random order and each participant swung the rods in  
118 this order. The test was carried out with a double blind protocol, where neither the  
119 participant nor observer knew the moment of inertia of the rod being swung.

#### 120 *Swing analysis*

121 Participants performed a maximal, internal rotation of the shoulder, keeping the elbow  
122 stationary, with the forearm swinging in the transverse plane. Each of the eight weighted  
123 rods was swung three times. Participants had a rest of one minute between swings to  
124 eliminate fatigue effects. To add a focal point and reduce unintentional deceleration,  
125 participants hit a ball suspended in front of them at the end of each swing. Any swings  
126 which did not visibly follow the desired motion were repeated, but these were not always  
127 easily identifiable.

128 To restrict the wrist joint, each participant wore a guard on their swinging arm; the wrist  
129 could not rotate to contribute to the movement. Participants also maintained a seated  
130 position to limit torso movement.

131 *Tracking*

132 A motion capture system was used to track swing kinematics. Twelve Motion Analysis  
133 Corporation Eagle cameras were used, recording at 300 frames per second with a shutter  
134 speed of 1 ms. The layout of the cameras with respect to the participant is shown in Figure  
135 2. The system had a residual error of  $6.24 \times 10^{-4}m$  in the position of markers in the 3D  
136 space.

137 Eight 12.7 mm spherical reflective markers were used to track the movement of the  
138 participant and the rod; their locations are shown in Figure 3. The markers were linked in  
139 the software such that the shoulder markers were connected to the Humerus and elbow  
140 markers; the elbow marker was connected to the Humerus, wrist and rod base markers and  
141 the wrist and rod base markers were connected to the rod tip.

142 Before swings were recorded each participant stood in a t-pose for a static trail after  
143 which the medial epicondyle marker (5) was removed. Maximum resultant velocity of the  
144 rod tip was the key variable of interest; other markers were used to review the movement  
145 and check adherence to the protocol.

146 The raw tracking files were initially processed using the Motion Analysis Cortex package.  
147 The cubic join function was used to fill in any short sections where the cameras had not  
148 seen a marker and the smooth function was used to reduce the noise of a trace. A  
149 Butterworth filter was used with a cut-off frequency of 10Hz.

150 *Kohonen self-organizing maps*



151 A self-organizing map (SOM) is an n-dimensional neural network which can be visualised  
152 as a 2D map of nodes. A SOM was used to ensure that only swings with good adherence to  
153 the desired movement pattern were considered in the analysis. This was necessary to  
154 ensure we made a fair comparison between individuals when analysing swing speed. SOM  
155 analysis has been used to categorise complex sporting movements in the past (Lamb,  
156 Bartlett, & Robins, 2010) and was used in a similar way here. A thorough description on the  
157 use of a SOM to investigate player technique is given in work by Lees (2002).

158 A vector, containing twelve variables, was used as the input to the SOM. These were the  
159 x, y and z positions of the shoulder, elbow and wrist joint centres during each swing and the  
160 3 angles between the Humerus and the global coordinate system axes. Each trial was  
161 normalised to 10 data points between the start of movement and peak tip velocity. A SOM  
162 was initialised and trained using the complete collection of input vectors, producing an 18 x  
163 12 hexagonal map. Each input vector (one for each swing) activated a 'trajectory' of up to  
164 ten activated nodes throughout the map (some points activate the same node). These  
165 trajectories were used to categorise every swing by dividing the map into sections. In Figure  
166 4a, the divisions of these sections have been overlaid onto a map showing how the  
167 Euclidean distance between nodes differs across the grid, with black representing a very  
168 short distance and white a large distance. Two nodes that have a short Euclidean distance  
169 between them represent a similar magnitude for each variable.

170 The trajectory analysis produced 2 distinct groups, which are represented in Figure 4b  
171 and Figure 4c. Figure 4b shows an example trajectory from group one, travelling from  
172 section 4 to section 2, and Figure 4c shows an example trajectory from group two travelling

173 from section 1 to section 5. Group one accounted for 41% of data and group two accounted  
174 for 31% of data. The remaining 28% of swings did not fit into either group.

175 The analysis was carried out using the SOM toolbox for MATLAB (Vesanto, Himberg,  
176 Alhoniemi, & Parhankangas, 2000).

177 A series of new versions of the self-organizing map were plotted, with each map showing  
178 the value of a selected variable at each node. As an example, Figure 5 shows a version of  
179 the map which has been shaded based upon each node's value of Elbow anterior-posterior  
180 position, relative to the direction the participant was facing. The paths of typical group one  
181 and group two trajectories were analysed and compared to the values of each variable on  
182 these maps. It can be seen on Figure 5 that group one trajectories exhibited very little  
183 change in anterior-posterior direction elbow position. Conversely, group two trajectories  
184 went through a large change from positive to negative, meaning the elbow was being  
185 translated in the posterior direction to help produce rod velocity, rather than just using  
186 rotation of the shoulder. After analysing all variables, it was decided that group one  
187 trajectories best matched the desired motion and only group one data were used for  
188 further analysis.

### 189 *Statistical tests*

190 The reduced data set produced by the self-organizing map method was plotted on log  
191 velocity – log moment of inertia graphs. In order to determine how well related the data  
192 were a 2-tailed Pearson correlation was run between the  $I_{Elbow}$  values and each participant's  
193 velocity data. The residual sum of squares was also calculated to assess the quality of fit in  
194 the data and the square root was taken to bring the units back to m/s.

195 **Results**

196 Figure 6 shows logarithmic plots of maximum rod tip velocity against  $I_{Elbow}$  for five  
197 participants. Almost 60% of the swing data was excluded as a result of the SOM analysis,  
198 and furthermore, a participant was only included if there was swing data for at least five of  
199 the eight rods. These strict criteria eliminated three participants from further analysis. With  
200 linear fits applied to each log-log plot,  $n$  values varied from 0.19 to 0.79.

201 The data in Table 2 shows the outcome of the Pearson's correlation test run between  
202  $I_{Elbow}$  and maximum swing velocity and the residual sum of squares for each participant.  
203 The five participants have a Pearson's correlation coefficient varying from -0.529 to -0.907  
204 and the rooted residual sum of squares varies from 0.0332 to 0.166. The maximum error in  
205 the value of  $n$  associated with the accuracy of the tracking system is  $\pm 0.08$ .

206 **Discussion and Implications**

207 The results in Figure 6 clearly show that the relationship between velocity and moment of  
208 inertia can be described using the power law in Equation 1. However, the  $n$  values are  
209 different for each participant in marked contrast with the results from previous studies  
210 (Cross & Bower, 2006; Daish, 1972; Smith et al., 2003). In these previous studies, the lines of  
211 best fit shown on the logarithmic plots of swing velocity against moment of inertia show  
212 near identical  $n$  values. Here, the participants have different  $n$  values and the velocity data  
213 only correlates strongly with moment of inertia for 2 of the 5 participants, as is shown in  
214 Table 2. The residual sum of squares values are mostly very low but are variable. Participant  
215 2 in particular has a high  $SS_R$  indicating a poor fit to the modelled trend line and this is  
216 evident in Figure 6.

217 The initial aim of this study was to observe whether or not there is a decaying relationship  
218 between swing speed and moment of inertia. Initial analysis found that this relationship  
219 exists but is different for different participants. As this finding contradicts the work of others,  
220 the dataset was further examined to understand whether the inter-participant differences  
221 were consistent.

222 For each rod, participants were ranked in order of their swing velocity. The participant  
223 with the highest swing velocity was ranked first, the participant with the second highest  
224 swing velocity was ranked second and so forth. The participant rank sets for each rod were  
225 then placed in order of their respective moment of inertia ( $I_{Elbow}$ ).

226 If the lines of best fit in Figure 6 had similar  $n$  values one would not expect the participant  
227 rankings to change between rods. Conversely, if the  $n$  values were variable (as in this study)  
228 one would expect the rank sets to change. A Spearman test was implemented to determine  
229 how similar the participant rank sets were as  $I_{Elbow}$  increased. The test was run between  
230 pairs of rank sets in order of increasing moment of inertia, comparing the rankings for rod 2  
231 with the rankings for rod 1 and so forth. A Spearman's rank correlation coefficient of 'one'  
232 indicates that consecutive rank sets are identical; a coefficient of 'zero' indicates that they  
233 are unrelated.

234 In order to confirm that the exclusion method was valid, the ranking analysis was firstly  
235 carried out for all eight participants and then repeated for the reduced dataset as specified  
236 by the self-organising map method.

237 Figure 7a shows the Spearman coefficients for all swing trials (no exclusions). It can be  
238 seen that there is no clear trend, and the rank sets change in a seemingly random pattern.  
239 Conversely, Figure 7b shows the Spearman coefficients the reduced data set.

240 There are distinct differences between the Spearman's rho values for the full data set and  
241 the reduced data set. There is a greater consistency in the reduced data set with the higher  
242 moment of inertia rods having values of 1.0. This clearly demonstrates the effectiveness of  
243 the exclusion criteria and justifies the decision to only analyse swings that adhered to a  
244 consistent technique.

245 Whilst the Spearman's rank correlation coefficient fluctuates for the low moment of  
246 inertia rods, it rests at a consistent value of 'one' for the high moment of inertia rods. This  
247 suggests that participants swing a low moment of inertia implement in an unpredictable  
248 manner, and it is only at higher moments of inertia where a clear pattern of behaviour  
249 becomes established. There can also be interactions with other swing criteria such as swing  
250 accuracy and it has been shown that swing accuracy peaks at lower speeds when swinging  
251 unfamiliar implements (Beilock, Bertenthal, Hoerger, & Carr, 2008).

252 It would be of value, for customisation purposes, to be able to predict swing speed for a  
253 given MOI. This may be possible if  $n$  is constant, which results suggest will be the case for a  
254 higher range of MOI. Aside from swing speed, the impact characteristics in racket sports are  
255 also important performance parameters influenced by moment of inertia. It has been shown  
256 that an increase in moment of inertia can cause an increase in outbound ball velocity (Brody,  
257 1997). This produces a trade-off in performance when changing moment of inertia and  
258 should yield an optimum MOI value. It is important to understand this optimum value and  
259 whether it changes for individual players of different strengths, as this could allow for  
260 customisation.

261 The consistency of the rankings at higher moment of inertias supports the hypothesis that  
262 for these participants, and a higher range of MOI in racket sports, it should be possible to  
263 predict a participant's swing speed. This may be achievable using some measures of physical

264 profile, for example joint torque or even standing height, which has been shown to relate  
265 well with serve speed in tennis (Vaverka & Cernosek, 2013). Conversely, it may not be  
266 possible for lower moment of inertia implements where there is a less consistent ranking of  
267 swing speed.

268 However, this is based on data for only one specific motion and many complex  
269 movements take place in all sports. Therefore a larger study with more participants would  
270 be required to understand how consistently swing speed is affected by moment of inertia  
271 for a higher range of MOI. Work should also be undertaken to look at whether MOI and  
272 physical profile can be used to predict an individual's swing speed as this knowledge will be  
273 of value to individuals wishing to customise equipment. This work could also be developed  
274 to consider a wider range of motions and to explore whether swing accuracy is adversely  
275 affected by changing moment of inertia.

## 276 **Conclusion**

277 This study found that for all participants, swing speed decreased with respect to increases  
278 in moment of inertia according to a power law. However, in marked contrast to previous  
279 studies, the rate of decrease varied from participant to participant.

280 It was found that participants swung the high moment of inertia rods in a more consistent  
281 manner than the low moment of inertia rods. This suggests that predicting a player's swing  
282 speed may not be easily achievable for very low moment of inertia implements common in  
283 racket sports but could be feasible for higher moment of inertia implements.

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- 340



341 **Tables**

342 **Table 1. Balance point,  $L_{cm}$ , and MOI,  $I_{rod}$ ,  $I_{Elbow}$  of the rods, all of which have length of**  
 343 **0.506m, mass of 0.32kg.**

Rod	$L_{cm}$	$I_{rod}$	$I_{Elbow}$
	(m)	(kgm <sup>2</sup> )	(kgm <sup>2</sup> )
1	0.129	0.0113	0.0569
2	0.164	0.0130	0.0587
3	0.197	0.0169	0.0626
4	0.233	0.0199	0.0656
5	0.263	0.0261	0.0718
6	0.300	0.0332	0.0789
7	0.340	0.0425	0.0882
8	0.372	0.0495	0.0952

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347

348 **Table 2. Correlation coefficients and residual sum of squares for the five participant's**  
 349 **velocity data and rod moment of inertia.**

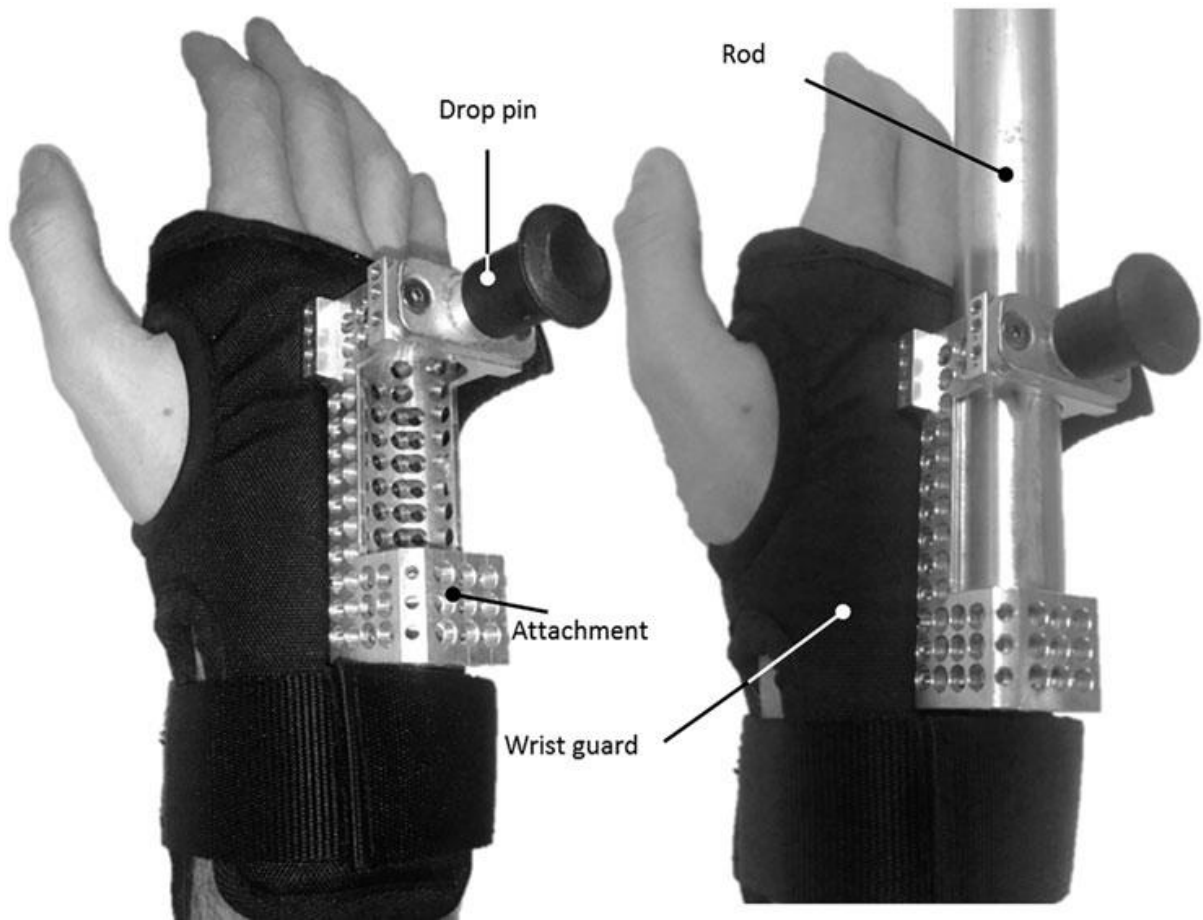
Participant	1	2	5	6	8
Pearson	-0.629	-0.529	-.907*	-.756*	-0.605
Correlation					
Significance	0.130	0.178	0.033	0.049	0.203
N	7	8	5	7	6
$\sqrt{SS_R}$ (m/s)	0.0878	0.166	0.0548	0.0332	0.0447

350 \*. Correlation is significant at the 0.05 level (2-tailed).

351

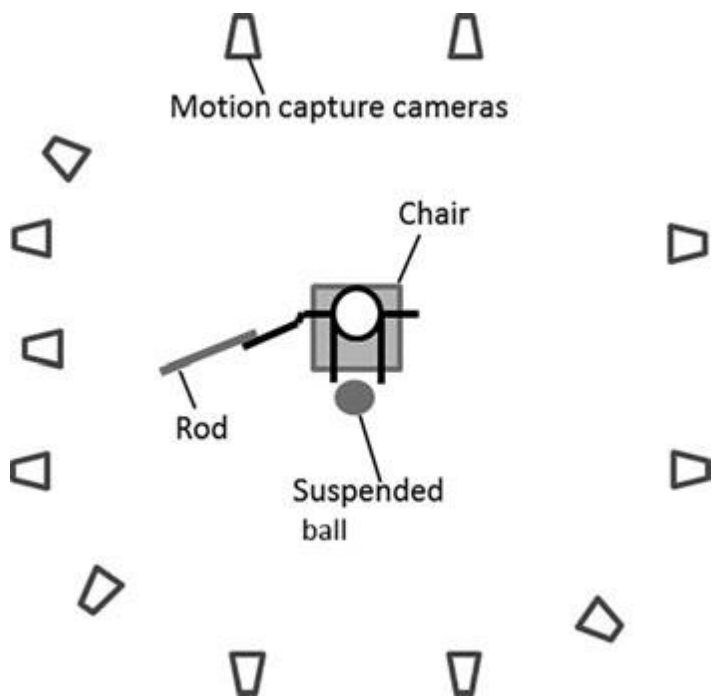
352

353 **Figure captions.**



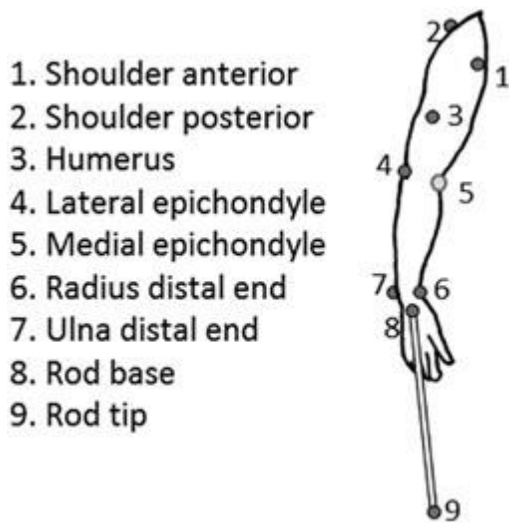
354

355 **Figure 1. Illustration of attachment mechanism**



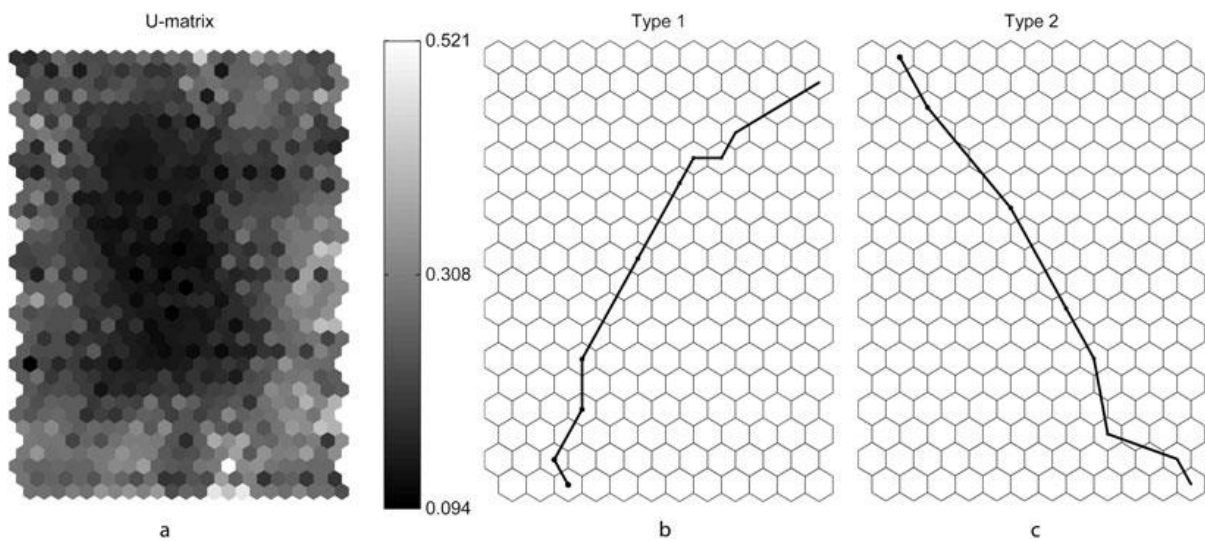
356

357 **Figure 2. Overhead view of experimental setup**



358

359 **Figure 3. Marker arrangement**

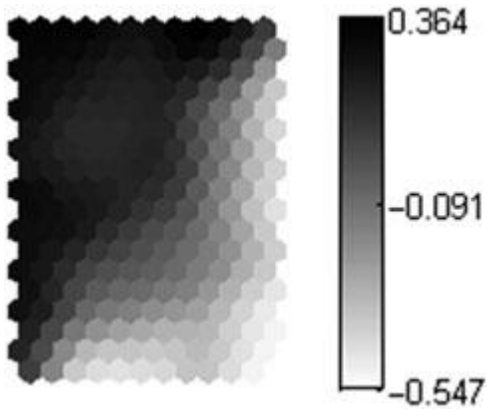


360

361 **Figure 4. SOM trajectories. *a*: U-matrix showing Euclidean distance between nodes with**

362 **section boundaries overprinted; *b*: example group one trajectory; *c*: example group two**

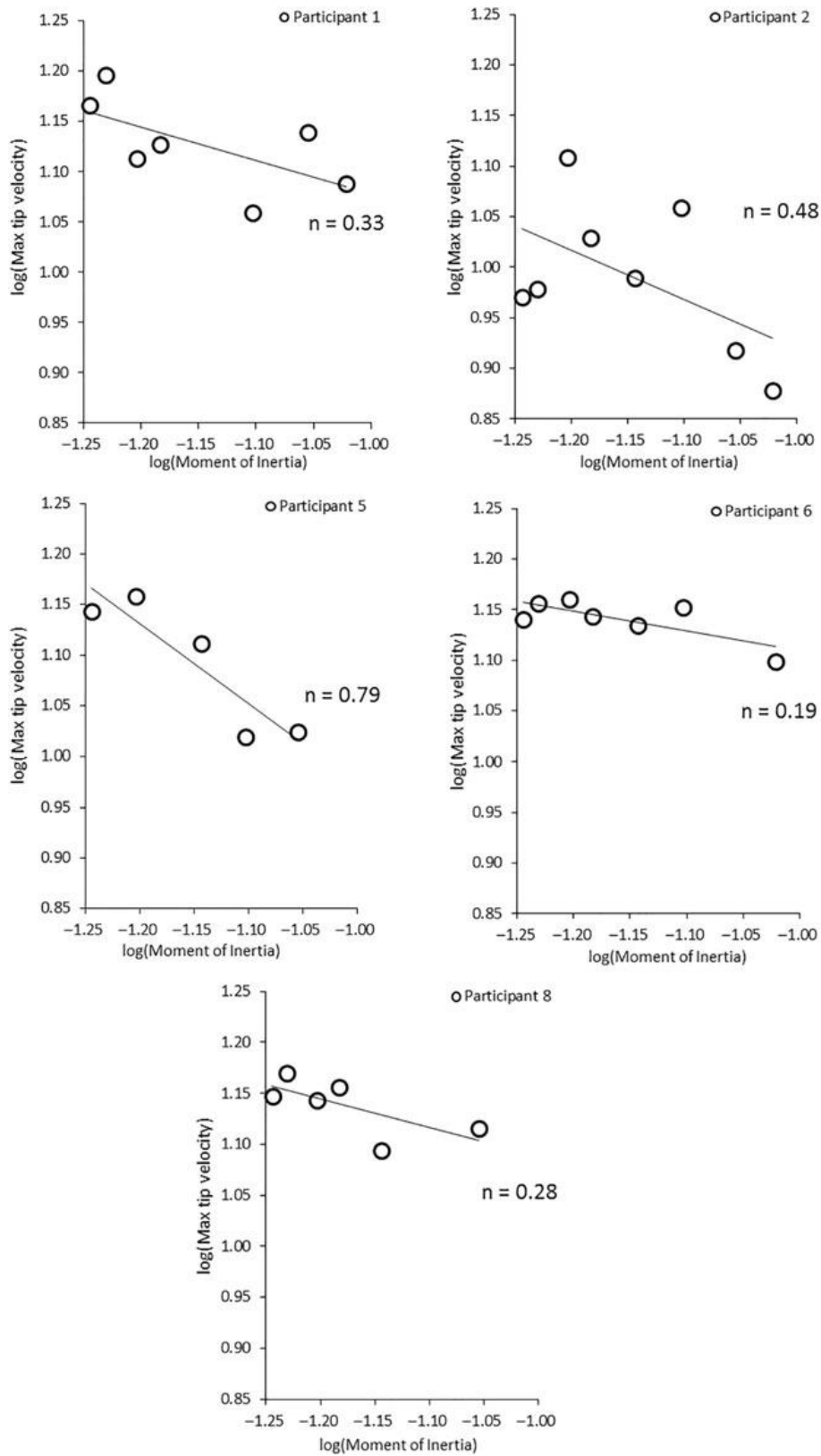
363 **trajectory.**



364

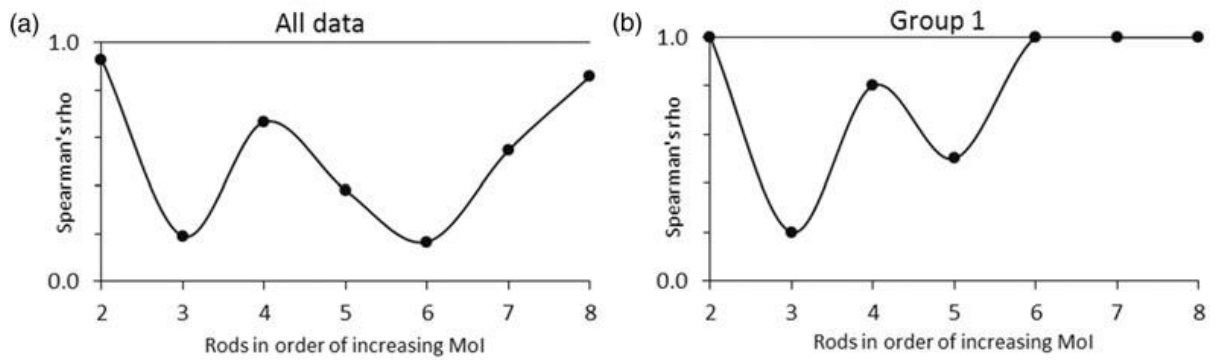
365 **Figure 5. A version of the self-organising map showing values of elbow position anterior-**

366 **posterior position.**



367

368 **Figure 6. Logarithmic plots of maximum rod tip velocity against moment of inertia.**



369

370 **Figure 7. Comparison of participant rank sets between rods of increasing moment of**

371 **inertia, for all data (a) and the data with exclusions applied (b).**

372