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

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20

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Introduction

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

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

In previous studies, the participants performed a motion typical to the sport being considered – skill and experience were important factors in the selection of participants in these studies. Each participant performs at different levels of consistency and habitually 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^2). 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
$$V = \frac{C}{I_o{}^n} \qquad \qquad (1)$$

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.

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

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

Methods

This study used a motion capture system to record the speed of weighted rods swung by 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 ± 5.4 years, mass of 73.3 ± 16.5 kg and

93   height of 1.79 ± 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 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.

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 ±0.08.

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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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^2)	(kgm2)
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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348 **Table 2. Correlation coefficients and residual sum of squares for the five participant's**

349 **velocity data and rod moment of inertia.**

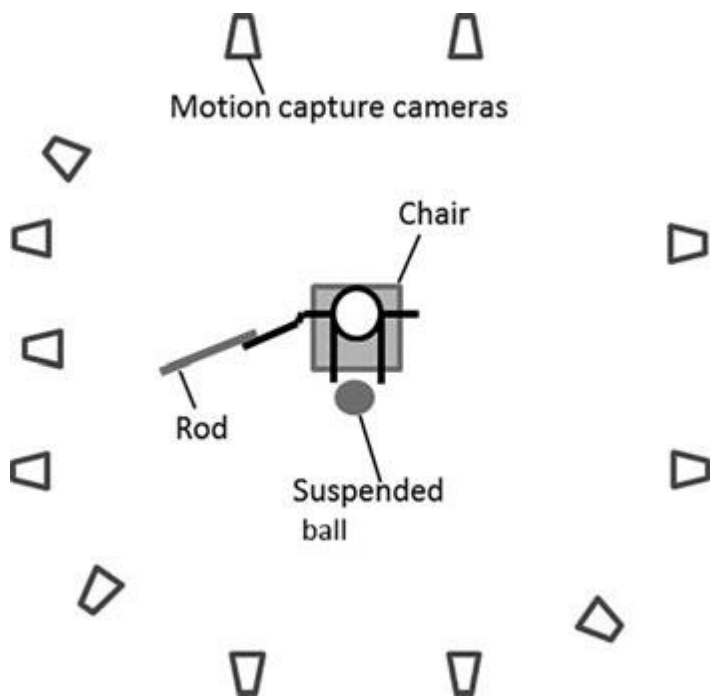| Participant	1	2	5	6	8
Pearson Correlation	-0.629	-0.529	-.907*	-.756*	-0.605
Significance	0.130	0.178	0.033	0.049	0.203
N	7	8	5	7	6
$\sqrt{SS_R}$ (m/s)	0.0878	0.166	0.0548	0.0332	0.0447

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

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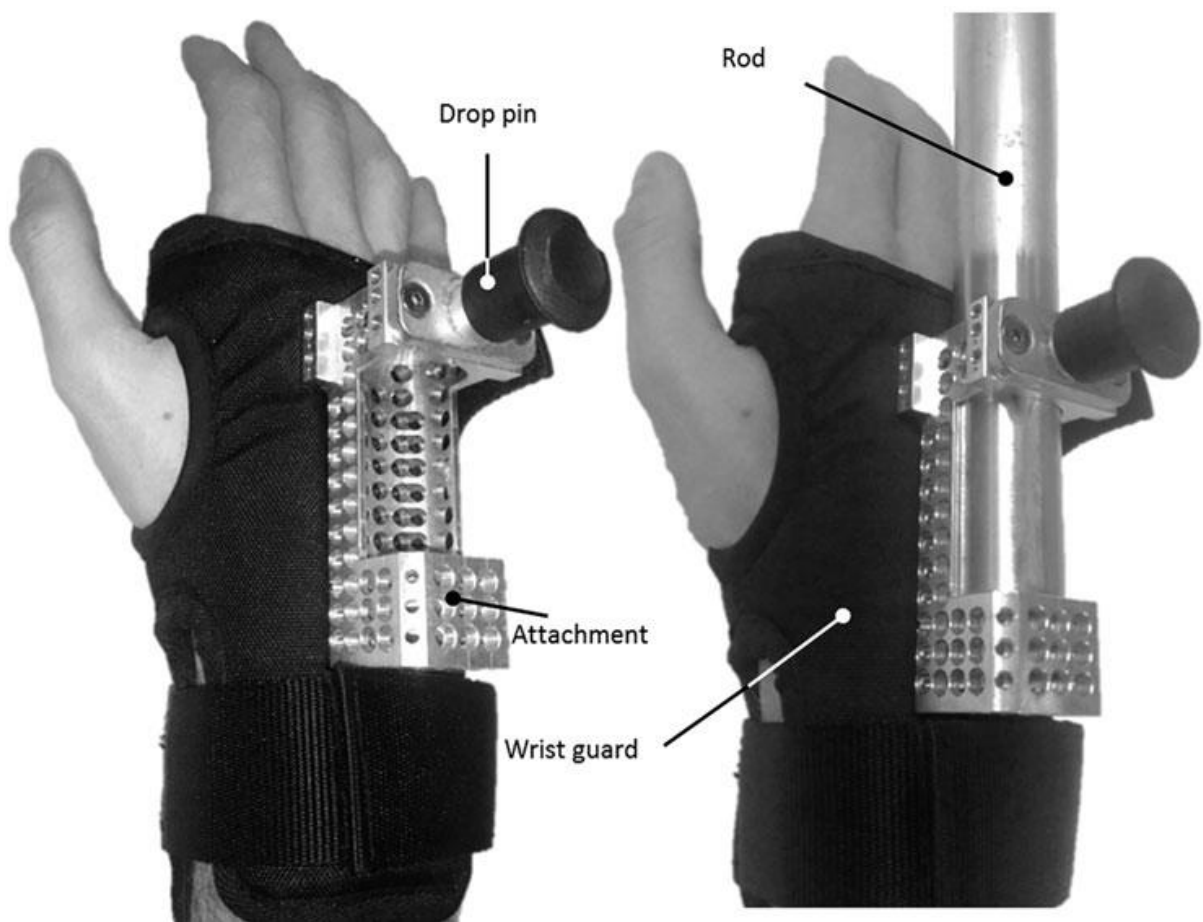
Figure 1. Illustration of attachment mechanism

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Figure 2. Overhead view of experimental setup

1. Shoulder anterior
2. Shoulder posterior
3. Humerus
4. Lateral epichondyle
5. Medial epichondyle
6. Radius distal end
7. Ulna distal end
8. Rod base
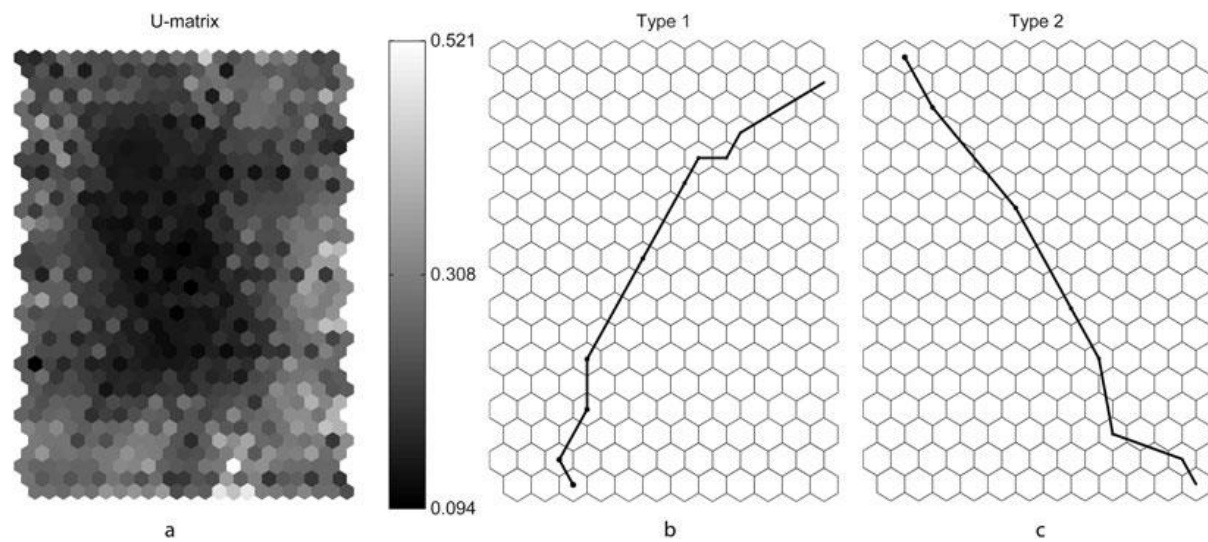9. Rod tip

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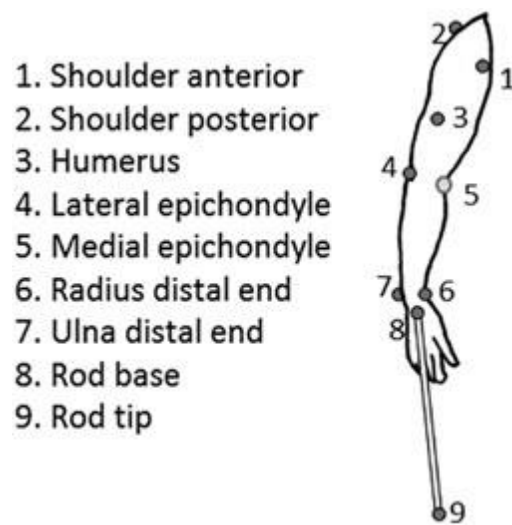
Figure 3. Marker arrangement

Figure 4. SOM trajectories. *a*: U-matrix showing Euclidean distance between nodes with section boundaries overprinted; *b*: example group one trajectory; *c*: example group two trajectory.
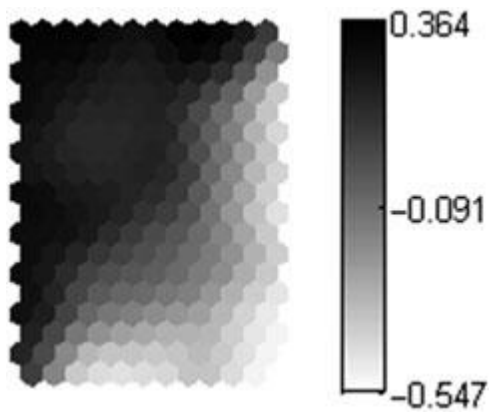
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365 **Figure 5. A version of the self-organising map showing values of elbow position anterior-**

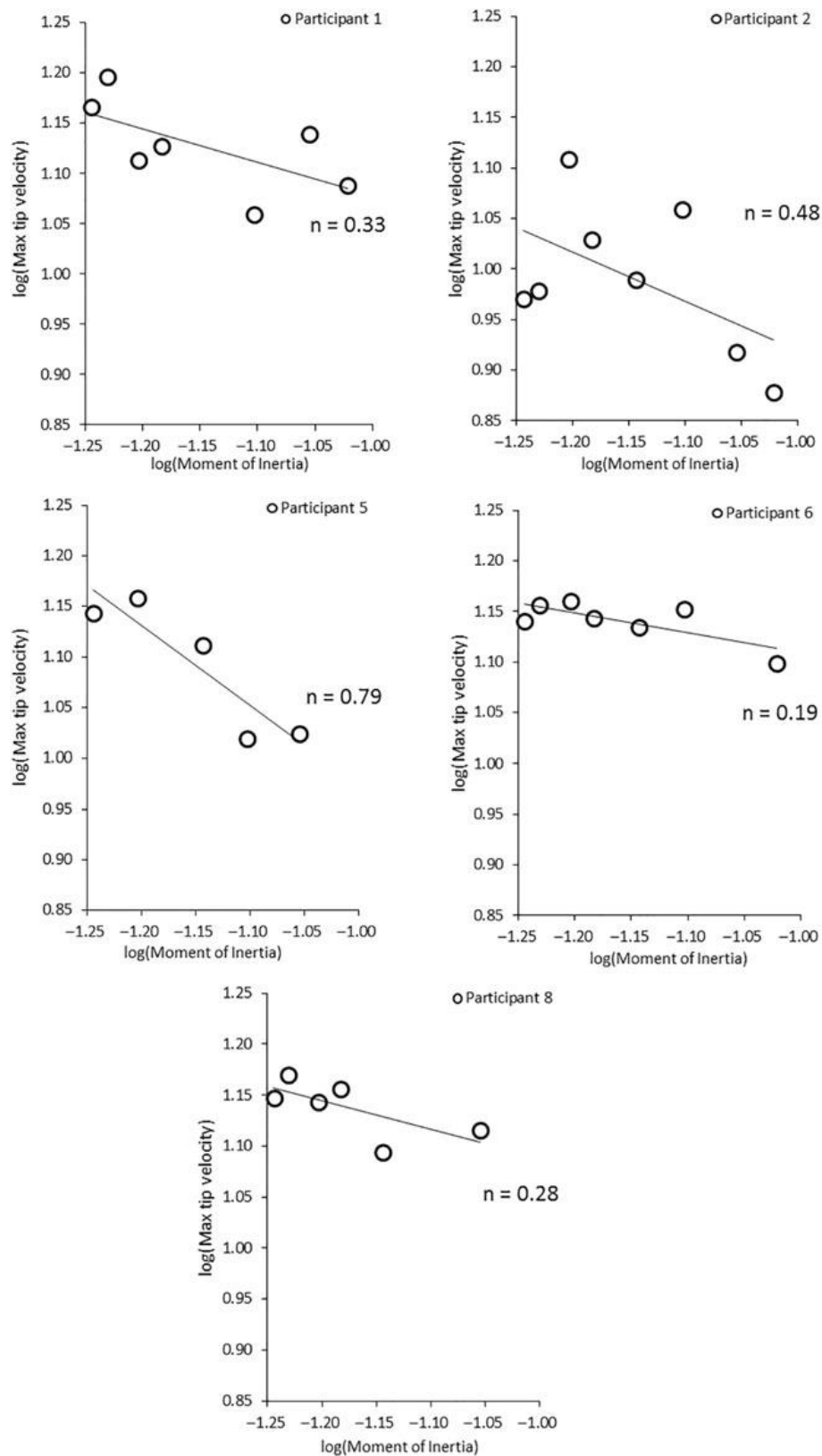366 **posterior position.**

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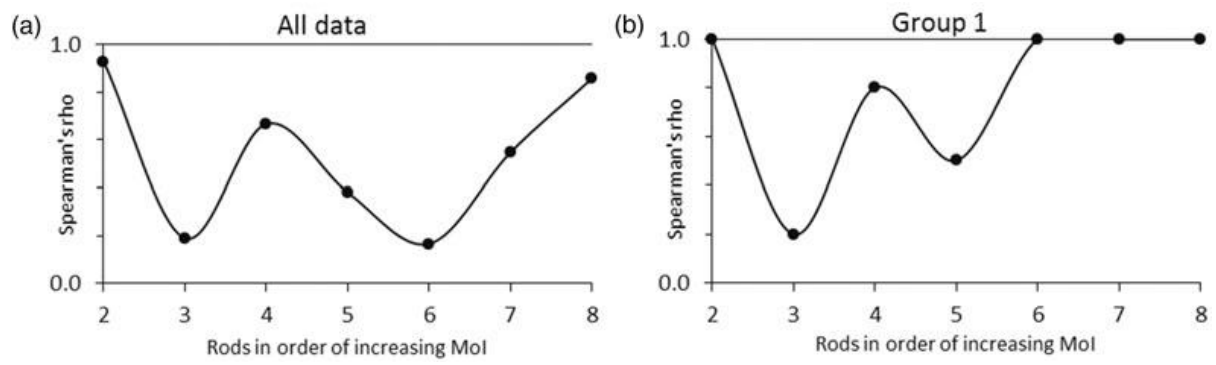**Figure 6. Logarithmic plots of maximum rod tip velocity against moment of inertia.**

Figure 7. Comparison of participant rank sets between rods of increasing moment of inertia, for all data (a) and the data with exclusions applied (b).