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## Explosive voluntary torque is related to whole-body response to unexpected perturbations

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1 **TITLE PAGE**

2

3 **Title:**

4 Explosive Voluntary Torque is Related to Whole-body Response to Unexpected  
5 Perturbations

6 **Authors:**

7 Fearghal P. Behan<sup>1,2,3</sup>, Matt T.G. Pain<sup>2</sup>, Jonathan P. Folland<sup>1,2</sup>

8 **Affiliations:**

9 <sup>1</sup>Arthritis Research UK Centre for Sport, Exercise and Osteoarthritis, Loughborough  
10 University, Leicestershire, UK.

11 <sup>2</sup>School of Sport, Exercise, and Health Sciences, Loughborough University, Leicestershire,  
12 UK.

13 <sup>3</sup>Research Department, Aspetar Sports Medicine Hospital, Doha, Qatar.

14

15 **Corresponding Author:**

16 Fearghal P. Behan. School of Sport, Exercise, and Health Sciences, Loughborough  
17 University, Leicestershire, UK, LE11 3TU. Email: F.Behan@lboro.ac.uk.

18

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20 and article drafting and revising. All authors have read and approved the final submitted  
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22

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25

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27 **Abstract**

28 Explosive torque has been demonstrated to relate to static balance. However, sports injuries  
29 occur dynamically and unpredictably, yet the relationship between explosive torque and  
30 balance response to dynamic perturbations is unknown. This study investigated the  
31 relationship between explosive torque of the plantar flexors and knee extensors and the centre  
32 of mass (COM) response to unexpected perturbations. Thirty-three healthy subjects (17  
33 females, 16 males) were assessed for maximal and explosive isometric knee extension (KE)  
34 and plantar flexion (PF) torque and COM response (velocity (COMV), displacement  
35 (COMD)) to unexpected platform translations. Relationships between explosive torque and  
36 balance measures were investigated using Pearson's correlation and multiple regression. A  
37 negative relationship between PF explosive torque at 50, 100, and 150 ms and COMV at 300,  
38 400, and 500 ms ( $r = -0.363$  to  $-0.508$ ,  $p \leq 0.049$ ), and COMD at 400 and 500 ms ( $r = -0.349$  to  $-$   
39  $0.416$ ,  $p \leq 0.046$ ) was revealed. A negative relationship between KE explosive torque at 50,  
40 100, and 150 ms and COMV at 400 ms ( $r = -0.381$  to  $-0.411$ ,  $p \leq 0.029$ ) but not COMD was  
41 also revealed. Multiple regression found PF 100 ms predicted 17.3% of variability in COMD  
42 at 500 ms and 25.8% of variability in COMV at 400 ms. These results suggest that producing  
43 torque rapidly may improve COM response to unexpected perturbation.

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## 52 **Introduction**

53 Sporting participation has obvious physical, social and psychological benefits but contains  
54 significant musculoskeletal injury risk (Bahr and Holm, 2003). An anterior cruciate ligament  
55 (ACL) rupture is one of the most common and costly sports injuries (Domire et al., 2001). It  
56 has been estimated that an ACL injury ages the knee 30 years and individuals who suffer a  
57 knee injury are at a more than 5-fold greater increase of developing osteoarthritis (Butler et  
58 al., 2008). Therefore, investigating potential contributors to injury mechanisms that may  
59 guide novel preventative strategies remain important.

60

61 ACL injuries occur within 50 ms of foot contact (Krosshaug et al., 2007) thus the ability to  
62 produce muscular force rapidly may be important in stabilising joints and preventing  
63 injurious positions (Zebis et al., 2010). The muscular ability to produce force rapidly is  
64 commonly referred to as explosive torque/force (i.e. at specific time points) or rate of  
65 torque/force development (RTD/RFD; i.e. gradient over specific periods). Explosive torque  
66 has been investigated in many populations (males, females, elderly, performance athletes)  
67 and demonstrated to be a determinant of athletic performance (Tillin et al., 2013; West et al.,  
68 2011). Post ACL repair, the ability to produce torque explosively has been demonstrated to  
69 predict hopping and vertical jump performance (Pua et al., 2017), to display larger  
70 asymmetries than maximal strength (Knezevic et al., 2014), and to be associated with self-  
71 reported knee function (Hsieh et al., 2014). However, there has been limited research into the  
72 relationship between explosive torque and balance performance. Explosive torque has been  
73 related to sway index ( $r = -0.559$ ,  $p = 0.010$ ) (Palmer et al., 2014) and RTD to balance  
74 measures in elderly subjects (Ema et al., 2016; Izquierdo et al., 1999]. RTD measures have  
75 also been found to predict tests that challenge lateral stability (Chang et al., 2005) and

76 discriminate between elderly fallers and non-fallers (Bento et al., 2010, Pjinappels et al.,  
77 2008). Collectively these results suggest that the ability to produce torque explosively may be  
78 related to balance performance and falls prevention.

79

80 Sports injuries occur in dynamic, unpredictable situations and often involve unexpected  
81 perturbations due to collision or impact (Krosshaug et al., 2007). Therefore, relationships  
82 between explosive force and static balance measures, such as sway index (Palmer et al.,  
83 2014), or premeditated balance tasks (Izquierdo et al., 1999) do not address the ability to  
84 control body position and balance in response to unexpected dynamic perturbations that  
85 occur within sports. Explosive torque has been demonstrated to improve dynamic balance  
86 recovery restricted to utilising the ankle strategy (Robinovitch et al., 2002) but has not been  
87 investigated with a whole-body response replicating the sporting environment. Accordingly,  
88 this study aimed to investigate whether knee extensor and plantar flexor explosive torque  
89 were related to the ability to stabilise the COM in response to unexpected perturbations. It  
90 was hypothesised that greater explosive muscular torque would be related to lower COM  
91 motions to unexpected perturbations.

92

93

## 94 **Methods**

### 95 *Participants*

96 Thirty-three healthy, young, participants (17 females: age  $22.9 \pm 3.1$ yr, height  $1.66 \pm 0.06$ m,  
97 mass  $65.0 \pm 8.3$ kg; 16 males: age  $24.7 \pm 5.1$ , height  $1.81 \pm 0.09$ m, mass  $81.1 \pm 9.5$ ) provided  
98 written informed consent prior to participating in this study, which was approved by the  
99 Loughborough University Ethical Approvals Committee. Participants had a BMI of  $\leq 26$   
100  $\text{kg}\cdot\text{m}^{-2}$ , no history of traumatic lower limb injury or current musculoskeletal condition and

101 were not involved in systematic physical training. Body mass and height were measured  
102 using a calibrated scale and stadiometer (Seca, Hamburg, Germany). All participants had  
103 moderate levels of physical activity as assessed by the International Physical Activity  
104 Questionnaire (iPAQ) (Craig et al., 2003). Participants were advised not to undertake any  
105 unaccustomed/strenuous physical activity for 36 hours prior to testing and to have eaten and  
106 drunk normally. To control for the possibility of menstrual cycle phase influencing  
107 neuromuscular performance during testing females were required to have been taking the  
108 combined monophasic oral contraceptive pill for >6 months and were tested between days 7  
109 and 21 of pill consumption to minimize any fluctuations in endogenous gonadal hormones  
110 (Pearson et al., 2011).

111

### 112 *Study Design*

113 This study used a cross-sectional study design. Participants visited the laboratory twice,  
114 separated by 5-10 days, for a familiarisation session and a main trial. Sessions commenced  
115 between 11.30am and 4.30pm. Familiarisation involved participants completing isometric  
116 contractions of the plantar flexors (PF) on an adapted commercial dynamometer and knee  
117 extensors (KE) on a custom built isometric strength testing chair; followed by familiarisation  
118 with dynamic perturbation testing. The main trial involved the same muscle function tasks of  
119 both legs unilaterally, first PF and then KE measurements, followed by assessment of the  
120 whole-body perturbation response to unexpected platform movements.

121

### 122 *Muscle Function Measurements*

123 Plantar Flexion: Participants were secured in an adapted commercial dynamometer (Con-trex,  
124 Dubendorf, Switzerland) in a kneeling position with a custom upright to support the anterior  
125 thigh, lock the proximal shank and minimise extraneous movement (Appendix 1A). The

126 dynamometer fulcrum was positioned in line with the lateral malleolus and the ankle was  
127 fixed at 90° and the knee at 120° (180° = full extension). Three ankle straps were secured  
128 tightly with a hip strap to further minimise any extraneous movements. The torque signal  
129 from the dynamometer was amplified (x1000) and sampled at 2000 Hz using an external A/D  
130 converter (Micro 1401; CED, Cambridge, UK) interfaced with a PC running Spike 2 software  
131 (CED Ltd., Cambridge, UK). In offline analysis, torque data were low-pass filtered at 500 Hz  
132 using a fourth-order zero-lag Butterworth filter.

133

134 Knee Extension: Participants were secured in a customised dynamometer (Maffioletti et al.,  
135 2016) with hip and knee joint angles of 125° and 115° respectively (Appendix 1B).  
136 Adjustable strapping across the pelvis and shoulders prevented extraneous movement. A  
137 strap, 40mm width of reinforced canvas webbing, was placed proximal to the ankle (~15% of  
138 tibial length above medial malleolus) in series with a calibrated S-beam strain gauge (Force  
139 Logic, Swallowfield, UK). The analogue force signal from the strain gauge was amplified  
140 (x370) and sampled at 2000 Hz using an external A/D converter (Micro 1401; CED,  
141 Cambridge, UK) interfaced with a PC running Spike 2 software (CED Ltd., Cambridge, UK).  
142 In offline analysis, force data were low-pass filtered at 500 Hz using a fourth-order zero-lag  
143 Butterworth filter, gravity corrected by subtracting baseline force, and multiplied by lever  
144 length (distance from ankle strap centre to knee joint space) to calculate torque (Balshaw et  
145 al., 2016).

146

#### 147 *Protocol*

148 Maximum Voluntary Isometric Contractions: Participants performed a series of warm-up  
149 contractions at ~50% and ~75% of perceived maximum voluntary torque (MVT) followed by  
150 three maximum voluntary contractions (MVCs) each lasting 3s with >30 s rest between.

151 Participants were instructed to contract as hard as possible and motivated with a standardised  
152 script of verbal encouragement and real-time visual biofeedback of the force response of each  
153 contraction. MVT was defined as the greatest torque during any MVC or explosive  
154 contraction.

155

156 Explosive Voluntary Isometric Contractions: Following a 2-minute rest post MVCs,  
157 participants completed 10 explosive KE and PF contractions, separated by 20s. They were  
158 instructed to contract ‘as fast and as hard as possible’ for 1s with ‘fast’ emphasized. To  
159 provide biofeedback on their explosive performance the slope of the force time curve was  
160 displayed throughout the contractions, with the peak slope of their best attempt highlighted.  
161 Contractions associated with pre-tension or a counter movement were discarded and  
162 repeated. A visual marker on screen depicted 80% MVT during the explosive contractions  
163 and participants were instructed to achieve this level in order to ensure a forceful contraction.  
164 Explosive contractions were performed until 10 contractions met criteria. Torque onset was  
165 defined manually by visual identification by one trained investigator; this involved viewing  
166 torque on an x axis scale of 300 ms prior to contraction and on a y axis scale of 0.68 N.m,  
167 before zooming in to determine the instant of the final trough or peak before the signal  
168 deflected away from the envelope of baseline noise (Balshaw et al., 2016). Explosive  
169 voluntary torque (EVT) was measured at discrete time points: 50, 100, and 150 ms from  
170 torque onset during the explosive contractions (e.g. PF 50, PF 100 etc.). All torque measures  
171 were normalised to body mass (kg) for correlations and regression analysis.

172

### 173 *Perturbation Response Testing*

174 Perturbation trials were completed on a CAREN system (Computer Assisted Rehabilitation  
175 Environment, Motek Medical, Amsterdam, Netherlands), a computer controlled Stewart



176 platform that can independently perturb the support surfaces in each of the six degrees of  
177 freedom. It has been found to be highly reliable for use in postural and balance research.<sup>19</sup>  
178 Prior to the perturbations 57 spherical markers of 14 mm diameter were attached to the  
179 participants to facilitate collection of kinematic data at 200 Hz using 9 T20 Vicon (Vicon,  
180 Oxford Metrics Group, UK) cameras. Whole-body segmental anthropometric measurements  
181 involved 45 measurements of each participant according to a reduced set inertial model  
182 (Yeadon, 1990). These were utilised to calculate participant-specific segmental inertial  
183 parameters for 15 body segments and used in the determination of joint centre locations and  
184 segmental and whole-body COM.

185

186 The COM position was defined relative to the centre of the platform, specifically the mean  
187 position of 4 markers located at the corners of the force plate. Participants were instructed to  
188 stand upright on the CAREN platform with hands by their side, the non-standing foot in a  
189 standardised position, the forefoot lightly touching the standing ankle, and asked to try to  
190 remain stationary and not to take a step in response to the perturbation. The perturbation  
191 commenced at random after participants had confirmed they were stable. Single leg standing  
192 was chosen to provide a sufficient balance stimulus. Four experimental conditions,  
193 sequentially in the following order: right foot/eyes open, left foot/eyes open, right foot/eyes  
194 closed, left foot/eyes closed, were completed with 16 trials per experimental set, resulting in  
195 64 trials per subject. The direction order of each perturbation (left, right, forward, backward)  
196 was block randomised so that 4 of each direction occurred in each experimental set. Only  
197 anterior platform displacements were analysed (including eyes open and closed) to assess  
198 sagittal plane muscle function, with the other directions interspersed to reduce predictability.  
199 This resulted in 16 anterior trials per participant, with the average of these trials used for  
200 analysis. The perturbations were controlled by a custom script written in the Motek Medical

201 D-Flow software. Anterior platform perturbations had a magnitude of 0.1 m and a maximum  
202 velocity of  $0.3 \text{ m}\cdot\text{s}^{-1}$  (Figure 1). The order of platform directional perturbations was selected  
203 randomly during pilot testing and was consistent for all participants. Data were low pass  
204 filtered with a fourth-order zero-lag Butterworth filter using a cut off frequency of 15 Hz.  
205 Initiation of perturbation was defined as when the velocity of the platform markers exceeded  
206  $0.005 \text{ m}\cdot\text{s}^{-1}$ . COM displacement and velocity (over 5 ms time periods) were obtained from the  
207 initiation of perturbation to 500 ms post perturbation using Visual3D software (C-motion,  
208 Germantown, MD, USA) with values at 100 ms intervals used for analysis. COM  
209 displacement (COMD) after the onset of the perturbation was measured relative to the initial  
210 position at onset of perturbation (defined as 0), and COM velocity (COMV) was defined as  
211 instantaneous velocity at each frame.

212

213

214

### 215 *Statistical Analysis*

216 Average measures across right and left legs were utilised for statistical robustness. The  
217 relationship of KE and PF MVT and EVT (at time points 50, 100, and 150 ms after  
218 contraction onset) with COMV and COMD values (100 ms intervals up to 500 ms) were  
219 investigated using Pearson's correlation coefficients. Subsequently stepwise multiple  
220 regressions were undertaken to examine the influence of the entered predictor variables  
221 (isometric strength parameters that displayed highest correlations with criterion variables)  
222 that independently explained a proportion of the total variance of COMD and COMV  
223 (criterion variables). Between subject coefficient of variation (CV) was obtained by  
224 calculating the ratio of the standard deviation to the mean. Statistical significance was

225 defined as  $p < 0.05$ . All statistical procedures were performed with IBM SPSS Statistics for  
226 Windows (Version 22.0, NY, USA, IBM Corp.).

227

## 228 **Results**

### 229 *Descriptive Data for Torque and Perturbation Measures*

230 EVT increased progressively throughout the first 150 ms of explosive contractions for both  
231 muscle groups: KE EVT rose from  $0.65 \text{ N.m.kg}^{-1}$  at 50 ms (CV 55%) to  $2.26 \text{ N.m.kg}^{-1}$  at 150  
232 ms (CV 32%) and PF EVT increased from  $0.38 \text{ N.m.kg}^{-1}$  at 50 ms (CV 42%) to  $1.82 \text{ N.m.kg}^{-1}$   
233 at 150 ms (CV 23%; Figure 2).

234

235 During the first 500 ms of anterior perturbations, the COMD relative to the base of support  
236 (the platform) at onset was increasingly posterior ( $0.005 \text{ m}$  at 100 ms (CV 23%) up to  $0.07 \text{ m}$   
237 after 500 ms (CV 15%), positive displacement value indicates posterior COMD).  
238 Consequently, there was an increasing posterior COMV during the initial phase of  
239 perturbation, on average peaking 300 ms after perturbation (CV 13%), before decreasing  
240 (decelerating) and becoming an anterior velocity after 500 ms (Figure 3).

241

### 242 *Bivariate Correlations of PF Torque with COMD and COMV*

243 PF EVT at all time points exhibited weak to moderate correlations with COMD in the later  
244 phase of the perturbation (PF 50 ms and COMD at 500 ms,  $r = -0.380$ ,  $p = 0.029$ ; PF 100 ms  
245 and COMD 400-500 ms,  $r = -0.349$  to  $-0.416$ ,  $p \leq 0.046$ , Figure 4A; PF 150 ms and COMD  
246 from 400-500 ms,  $r = -0.352$  to  $-0.406$ ,  $p \leq 0.044$ , Figure 5A). PF EVT at all time points also  
247 exhibited weak to moderate negative correlations with COMV in the later phase of the

248 perturbation (PF 50 ms and COMV 400- 500 ms,  $r = -0.421$  to  $-0.459$ ,  $p \leq 0.015$ ; PF 100 ms  
249 and COMV 400- 500 ms,  $r = -0.398$  to  $-0.508$ ,  $p \leq 0.022$ , Figure 4B; PF 150 ms and COMV  
250 300-500 ms,  $r = -0.346$  to  $-0.479$ ,  $p \leq 0.049$ ; Figure 5B). In contrast, PF MVT was unrelated  
251 to either COMV or COMD ( $r = -0.053$  to  $-0.246$ ,  $p \geq 0.167$ ).

252

### 253 *Bivariate Correlations of KE Torque with COMD and COMV*

254 KE EVT at 50, 100, and 150 ms showed weak to moderate negative correlations with COMV  
255 at 400 ms ( $r = -0.381$  to  $-0.411$ ,  $p \leq 0.021$ , Figure 6A) but not with any measures of COMD  
256 (Figure 6B). KE MVT was negatively correlated with COMV at 300 ms ( $r = -0.371$ ,  $p =$   
257  $0.033$ ) but not with COMD ( $r = -0.199$  to  $-0.288$ ,  $p \geq 0.104$ ).

258

### 259 *Multiple Regression Analysis*

260 The muscle function measurements that were the strongest predictors of perturbation  
261 response for each muscle group (PF 100 and KE 100) from the correlation analysis were  
262 subsequently included in a stepwise multiple linear regression analysis. PF 100 predicted  
263 17.3% of the variability in COMD at 500 ms and 25.8% of the variability in COMV at 400  
264 ms. KE 100 was not found to be a significant predictor of COMD or COMV within the  
265 multiple regression analysis.

266

## 267 **Discussion**

268 The present study investigated the relationship between the COM stabilisation  
269 (displacement/velocity) in response to unexpected anterior perturbations with both KE and  
270 PF explosive torque. PF EVT had weak to moderate correlations with COMD from 400-500  
271 ms ( $r = -0.346$  to  $-0.508$ ) and COMV from 300-500 ms ( $r = -0.349$  to  $-0.416$ ; i.e. more  
272 explosive torque less COMD and COMV), with weaker correlations between KE EVT and  
273 COMV at 400 ms ( $r = -0.381$  to  $-0.411$ ) but not with COMD. In contrast MVT of the PF and  
274 KE were unrelated to COMD and unrelated/ weakly related to COMV. Moreover, the  
275 regression analysis revealed PF 100 to be the only neuromuscular variable to independently  
276 contribute to the explained variance in COMD and COMV.

277

278 These findings suggest that greater explosive torque, particularly from the distal (PF)  
279 musculature, results in better control of the COM in response to unexpected perturbations. PF  
280 EVT explained up to 25.8% of the variability in the COMD following perturbation. Thus,  
281 while PF EVT was the primary neuromuscular determinant of the ability to respond to  
282 unexpected perturbation, the majority of the variance remained unexplained. Somatosensory  
283 and reflex responses might also be expected to contribute substantially to the perturbation  
284 response. Nonetheless, in the current study significant correlations were consistently found  
285 for explosive torque measured at a range of time points, with both COMV and COMD from  
286 300-500 ms indicating a genuine, systematic relationship.

287

288 Our findings of a negative relationship between explosive torque and COM response  
289 substantiates previous research that found higher explosive torque to be related to superior  
290 static or premeditated balance responses (Ema et al., 2016; Izquierdo et al., 1999; Jakobsen et  
291 al., 2011; Palmer et al., 2014; Sundstrup et al., 2010). In overview, there is accumulating  
292 evidence that lower limb explosive torque production may improve the ability to recover

293 balance and appears to be an important component of falls risk and injury prevention (Bento  
294 et al., 2010; Jakobsen et al., 2011; Sundstrup et al., 2010).

295

296 Repeated significant correlations were found between PF EVT and both COMV and COMD  
297 providing evidence of a consistent relationship, however, KE EVT only correlated with  
298 COMV at 400 ms and not with any COMD values, presumably because the KE did not  
299 sufficiently influence COMV to effect COMD. Furthermore, PF EVT was the only predictor  
300 of COM response in stepwise regression. Therefore, PF explosive torque appears more  
301 important in controlling dynamic perturbation response. The greater importance of the PF  
302 may be a consequence of a distal to proximal muscle activation pattern in response to  
303 perturbations, where postural muscle activation begins at the base of support (Alexander et  
304 al., 1992; Jakobsen et al., 2011; Sveistrup et al., 1997). A greater contribution of the ankle  
305 musculature and a lesser contribution of the knee musculature in achieving postural control in  
306 response to perturbation is in accordance with previous literature (Hall and Jensen, 2002;  
307 Jakobsen et al., 2011).

308

309 In contrast to PF explosive torque PF MVT was not correlated with either COMD or COMV.  
310 Other studies have also found weaker or no relationship for MVT and balance performance,  
311 compared to EVT (Bento et al., 2010; Izquierdo et al., 1999; Lee et al., 2009). As maximal  
312 torque can take more than 300 ms to produce it seems that explosive torque may be more  
313 pertinent in response to rapid stimuli such as unexpected perturbations and sports related  
314 injury mechanisms (Krosshaug et al., 2007; Sundstrup et al., 2010). The relationship between  
315 EVT, and not MVT, to perturbation response demonstrates that explosive torque production,  
316 rather than maximal torque, appears the most important neuromuscular characteristic in  
317 responding to rapid alterations to postural balance. Therefore, future interventions for

318 improving postural balance response may benefit from including specifically explosive  
319 strength training, rather than training for maximal strength.

320

321 Correlations between PF/KE explosive torque and COM response to perturbation only  
322 became significant from 300 ms onwards. The anterior platform perturbation caused the  
323 COM to initially move posteriorly relative to the base of support/platform (Nashner et al.,  
324 1979), before participants initiated a response to prevent the COM moving outside, and in  
325 this case posterior to, the base of support (Lin and Woolacott, 2002). Considering muscle  
326 response latency, potentially over 100 ms (Nashner et al., 1979) including sensory and  
327 neurological delays, followed by electromechanical delay (Blenkinsop et al., 2016), it is  
328 feasible that the initiation of compensatory muscular torque only commenced 150 ms after  
329 the perturbation. Thereafter muscular torque would have progressed rapidly to slow and  
330 ultimately reverse the posterior velocity of the COM imposed by the anterior platform  
331 displacement. This potential reversal of COMV consequently exhibited a reduction in COMD  
332 from 400 ms; implying reactive torque may have reduced the COM displacement from the  
333 perturbing mechanism.

334

335 Many sporting injuries, such as ACL injuries, are in response to an activity involving an  
336 initial contact, such as landing and changing direction (Krosshaug et al., 2007). Therefore,  
337 future research should attempt to replicate the current findings in a sporting specific scenario  
338 to confirm the relationship between explosive torque and kinematic responses following a  
339 task such as landing from a jump or changing direction. The current investigation may have  
340 been limited by utilising isometric contractions, while facilitating controlled measurements of  
341 maximum and explosive torque, this measurement may lack ecological validity to dynamic  
342 functional movement. The current findings would also have been more robust with a larger

343 number of participants. In conclusion, the ability to produce torque rapidly in the PF was  
344 moderately associated with the response to unexpected perturbations, predicting up to 26% of  
345 perturbation response. This indicates that higher explosive torque capacity, which can be  
346 developed through training (Balshaw et al., 2016), may be useful in responding to external  
347 collisions and disturbances of balance, and would be expected to reduce injury risk in  
348 sporting situations.

349

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352 Osteoarthritis.

353

### 354 **Conflict of interest statement**

355 This is to confirm the authors of this work have no conflicts of interest.

356

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**Figure 3.** Centre of mass (COM), (relative to centre of moving force plate) Displacement (A, black squares) and COM Velocity (B, black circles) for each time point (ms) post perturbation. Values are mean  $\pm$  SD (n = 33) with maximum and minimum values (dashed line). Positive values indicate posterior displacement/velocity.

**Figure 4.** Sample scatter plots of PF explosive torque at 100 ms and (A) COM Displacement at 400 ms and (B) COM Velocity at 400 ms (n = 33).

**Figure 5.** Pearson's product moment correlation coefficients between explosive torque of the plantar flexors (PF) at three time points (50, 100, 150) and centre of mass displacement (COMD, A) and centre of mass velocity (COMV, B) post perturbation (n = 33). Y axis inverted for ease of visualization.

**Figure 6.** Pearson's product moment correlation coefficient between explosive torque of the knee extensors (KE) at three time points (50, 100, 150) and centre of mass displacement (COMD) (A) and centre of mass velocity (COMV) (B) post perturbation (n = 33). Y axis inverted for ease of visualization.

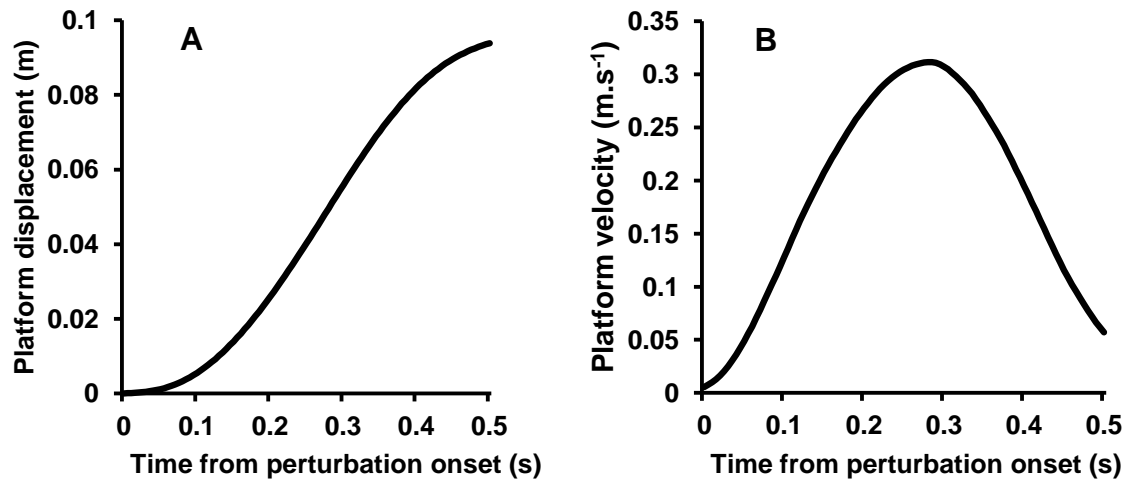


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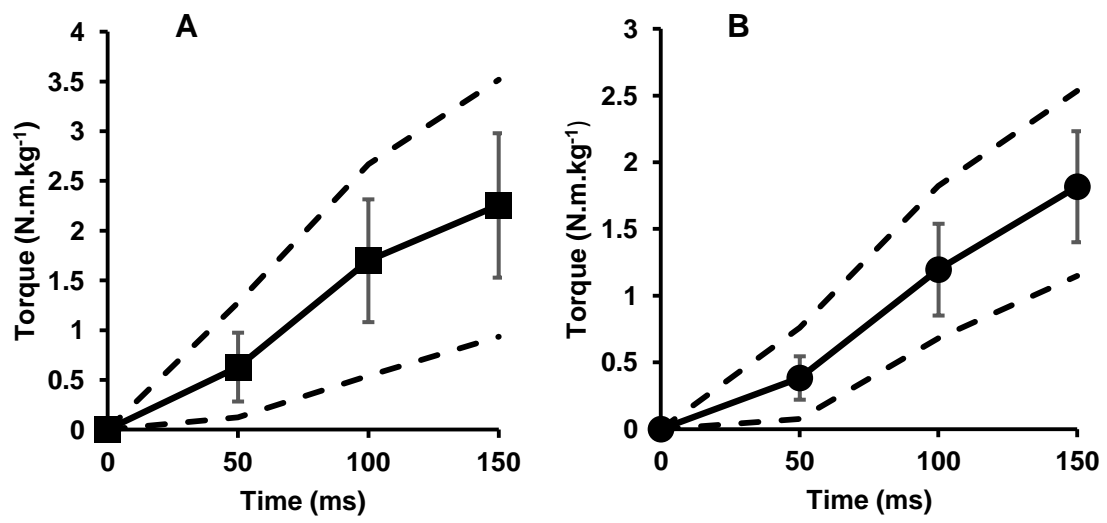


Figure 2.

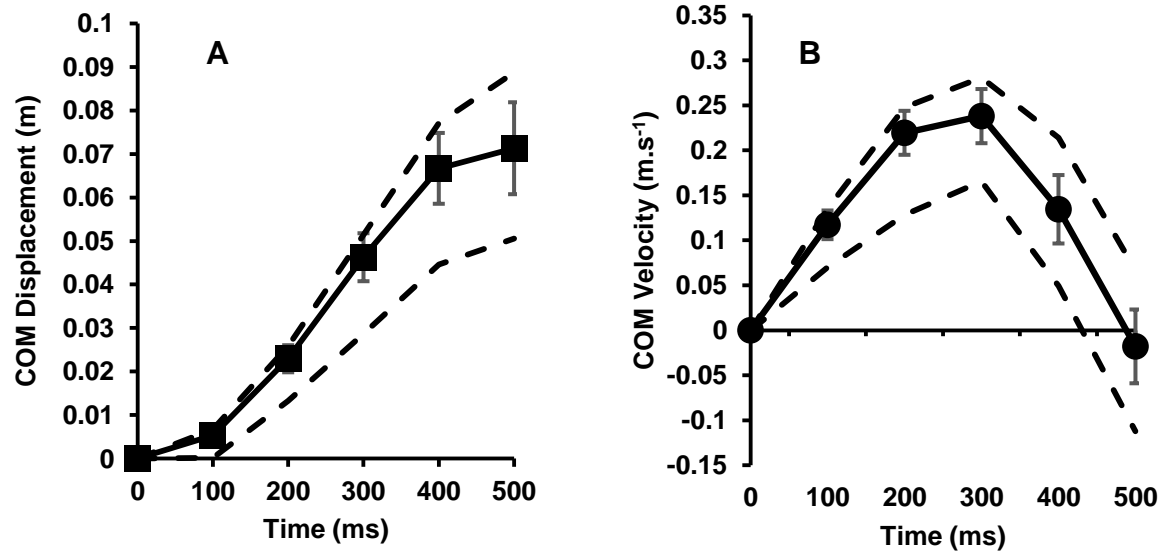


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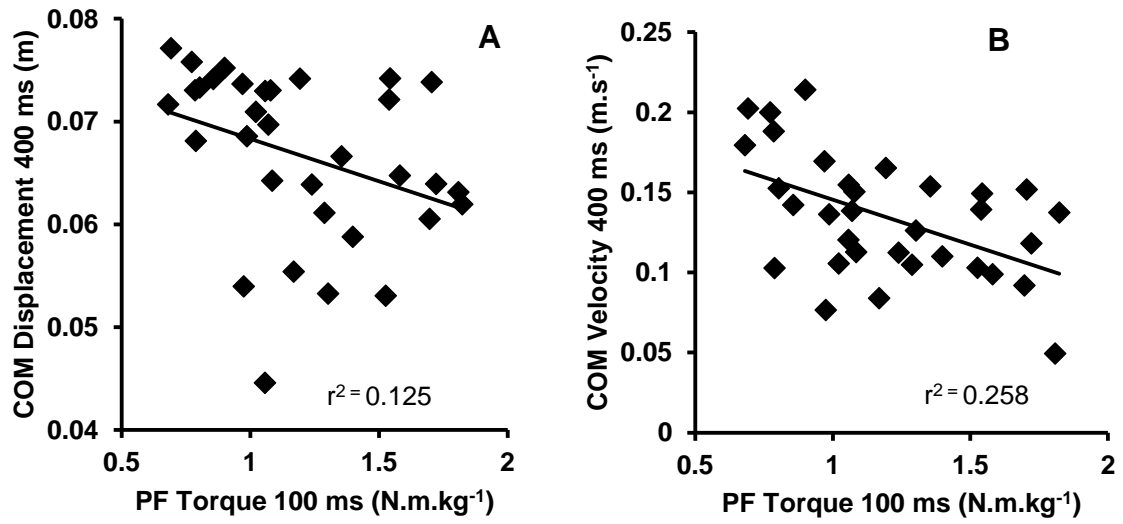


Figure 4.

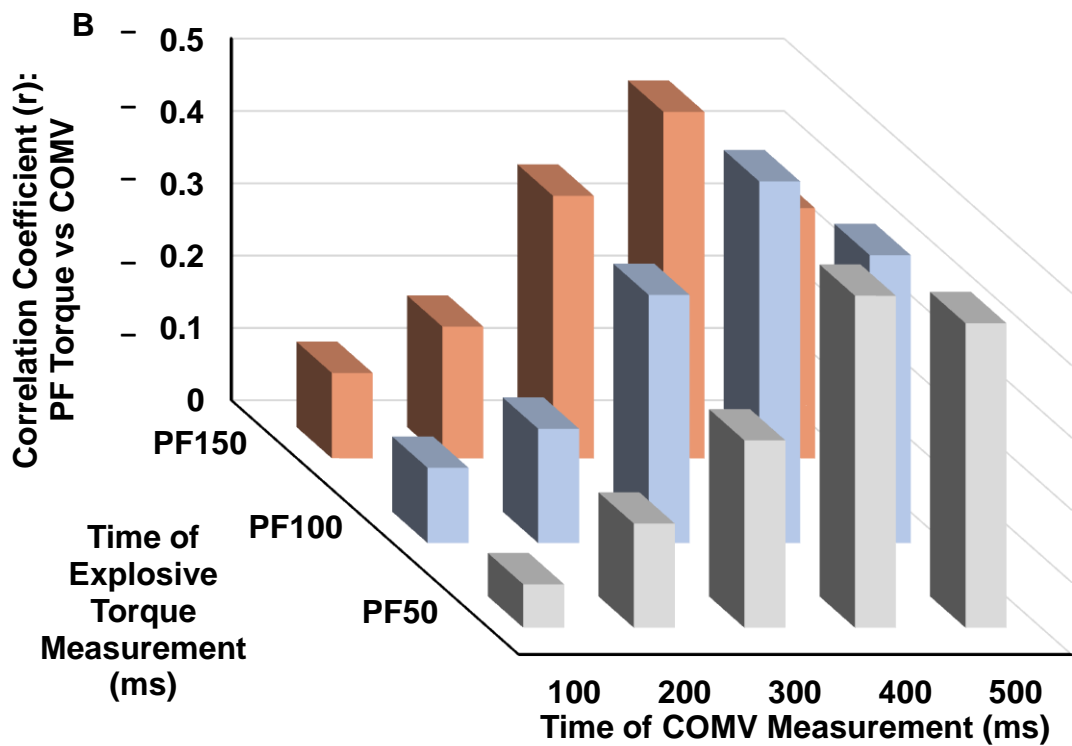
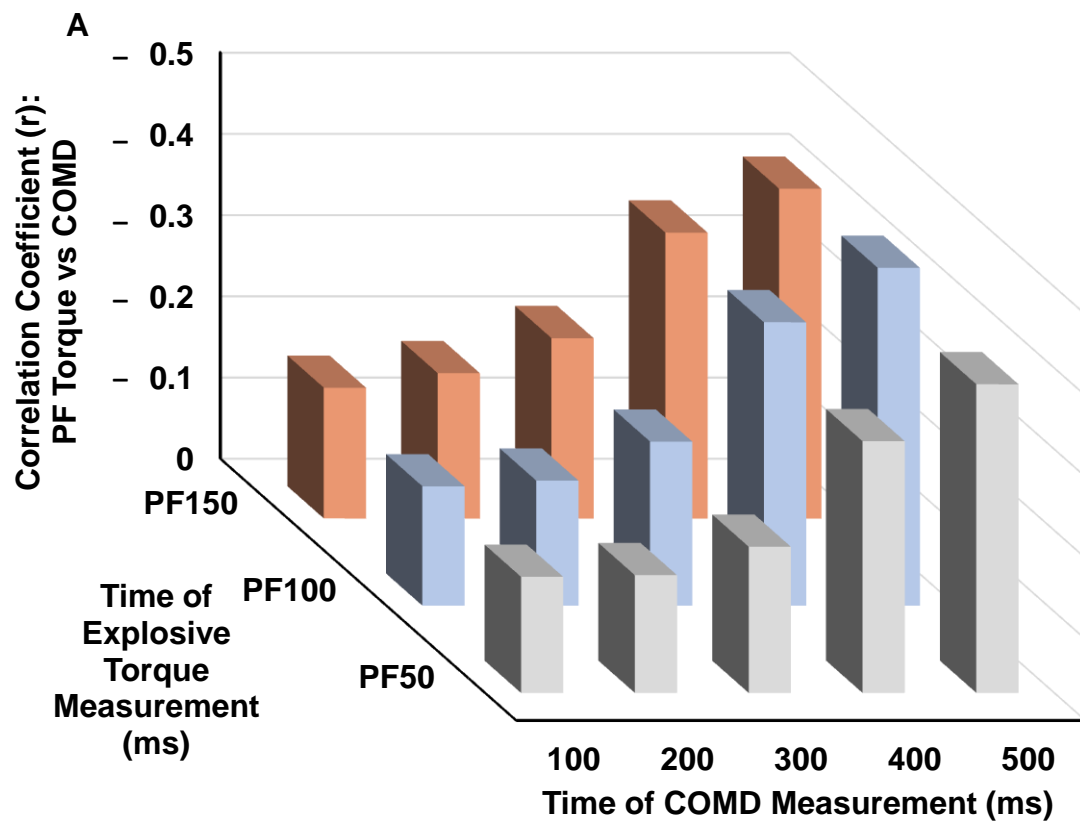


Figure 5.

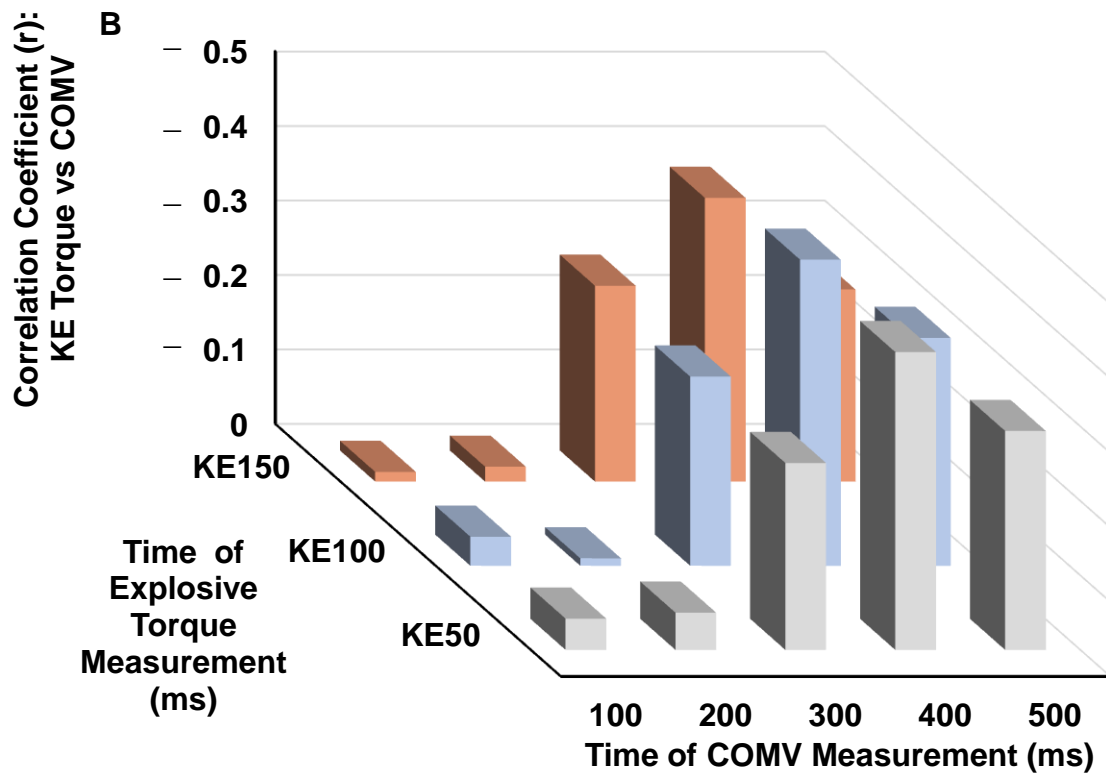
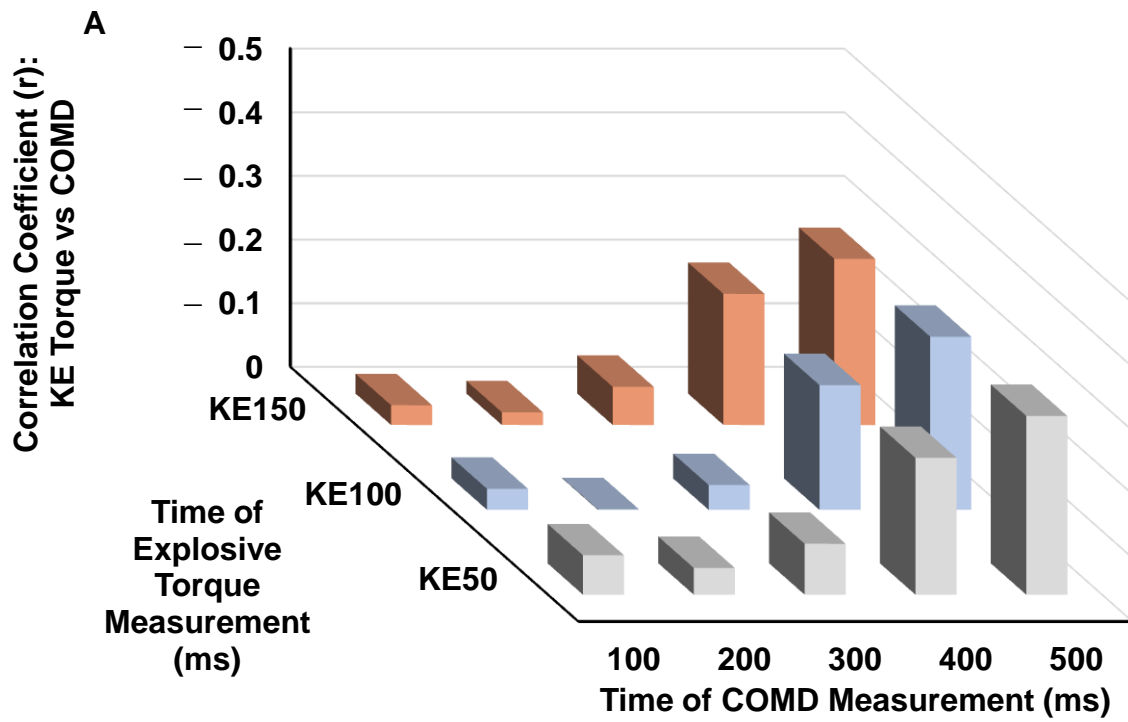
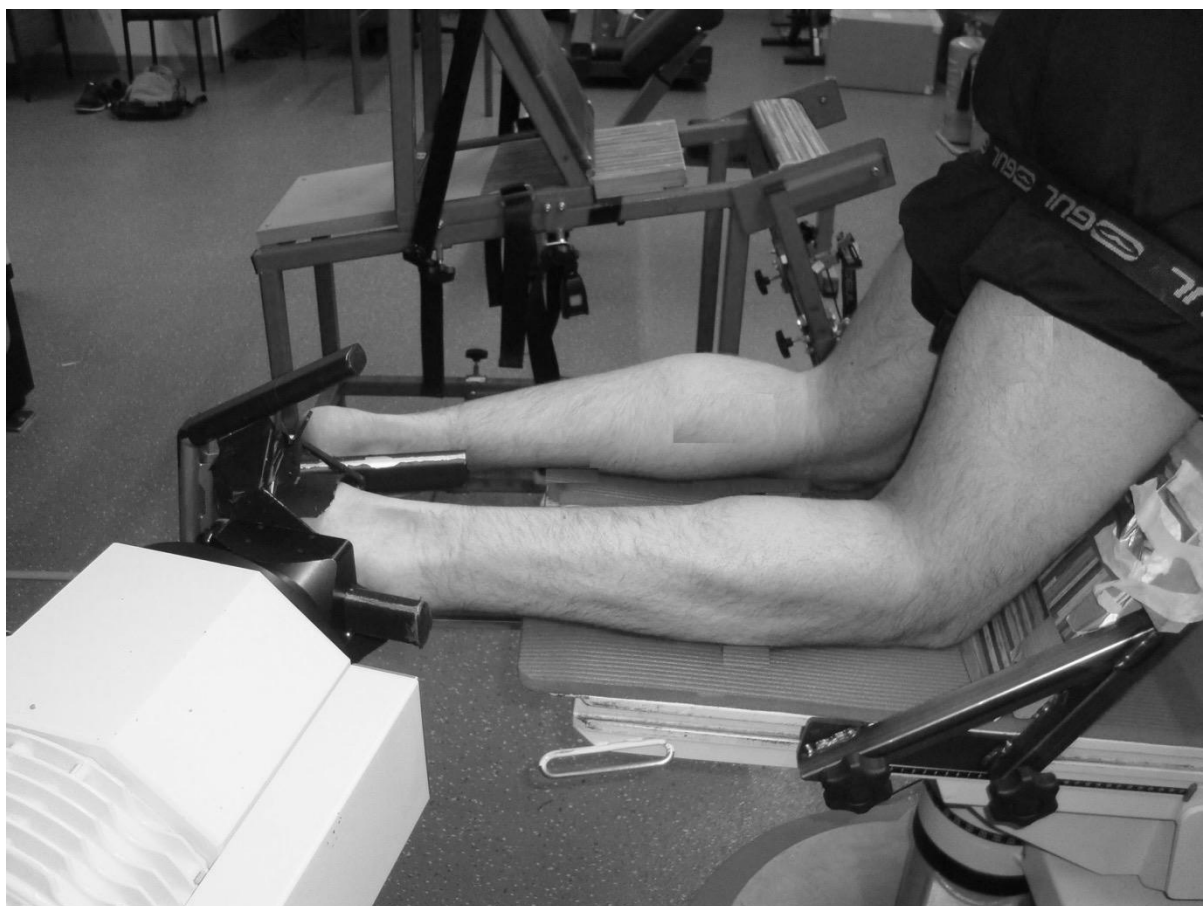
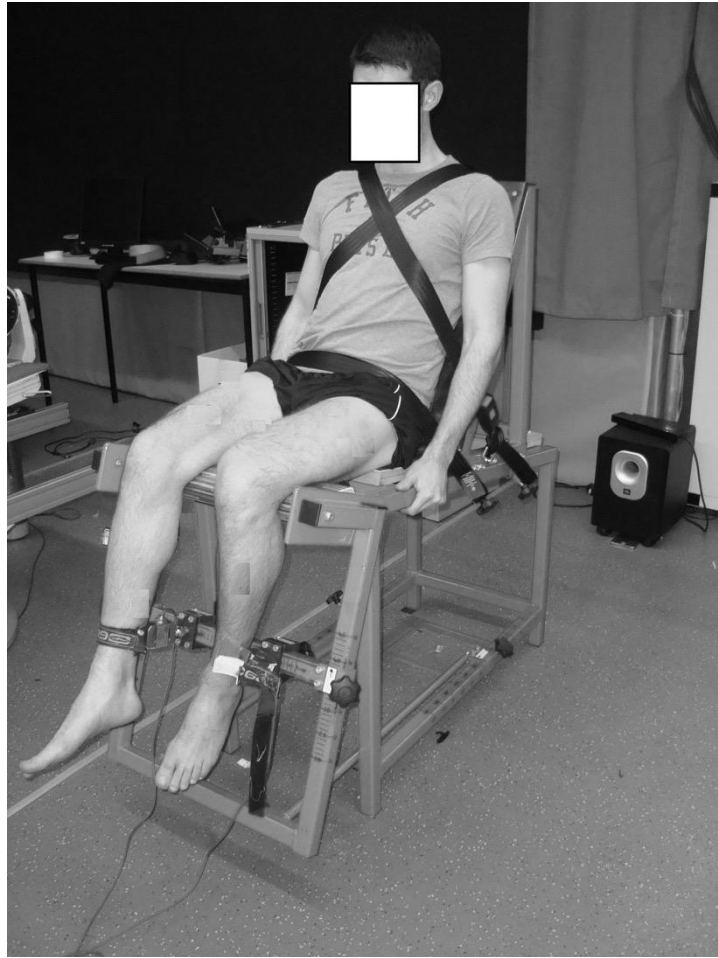


Figure 6.



**Appendix 1A.** Isometric maximum and explosive voluntary torque measurements of the plantar flexors with an adapted Con-trex isokinetic dynamometer.



**Appendix 1B.** Isometric maximum and explosive voluntary torque measurements of the knee extensors with a custom built isometric dynamometer.