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2 Hip and knee kinematics display complex and time-varying sagittal kinematics during

3 repetitive stepping: Implications for design of a functional fatigue model of the knee

4 extensors and flexors

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## Abstract

17 The validity of fatigue protocols involving multi-joint movements, such as stepping, has yet  
18 to be clearly defined. Although surface electromyography can monitor the fatigue state of  
19 individual muscles, the effects of joint angle and velocity variation on signal parameters are  
20 well established. Therefore, the aims of this study were to i) describe sagittal hip and knee  
21 kinematics during repetitive stepping ii) identify periods of high inter-trial variability and iii)  
22 determine within-test reliability of hip and knee kinematic profiles. A group of healthy men  
23 (N = 15) ascended and descended from a knee-high platform wearing a weighted vest  
24 (10%BW) for 50 consecutive trials. The hip and knee underwent rapid flexion and extension  
25 during step ascent and descent. Variability of hip and knee velocity peaked between 20-40%  
26 of the ascent phase and 80-100% of the descent. Significant ( $p < 0.05$ ) reductions in joint range  
27 of motion and peak velocity during step ascent were observed, while peak flexion velocity  
28 increased during descent. Healthy individuals use complex hip and knee motion to negotiate a  
29 knee-high step with kinematic patterns varying across multiple repetitions. These findings  
30 have important implications for future studies intending to use repetitive stepping as a fatigue  
31 model for the knee extensors and flexors.

32

33 *Keywords:* variability; biomechanics; functional; velocity; displacement

34

## 35 **Introduction**

36 The progression and effect of muscle fatigue on knee function during locomotion remains  
37 poorly understood due to limitations in monitoring dynamic muscle fatigue. The experimental  
38 design and the model used to define and monitor fatigue is a critical factor in determining  
39 fatigue-related changes in muscle function. The model comprises the muscles of interest, the  
40 exercise protocol, the measures used to quantify fatigue, the timing of measurement and the  
41 operational definition of fatigue <sup>1</sup>. The need to maximize external validity has prompted  
42 increased use of tasks that mimic occupational or sporting activities, such as jumping, squats  
43 or hopping <sup>2-4</sup>. Stepping onto a step is a functional movement performed frequently in  
44 occupational situations <sup>5</sup>. It requires high amounts of work performed by the hip and knee  
45 extensors to raise the body onto the raised surface. However, there is a lack of information  
46 regarding the internal validity of fatigue models involving functional tasks, such as stepping.  
47 Specifically, how effectively a task such as stepping induces fatigue in the quadriceps and  
48 hamstrings.

49

50 Monitoring fatigue onset and progression within the knee extensors and flexors during  
51 stepping is a complex undertaking. Surface electromyography (sEMG) has been used  
52 extensively for monitoring muscle fatigue in-vivo by detecting changes in the muscle  
53 activation signal <sup>6,7</sup>. In particular, the spectral shift of the sEMG signal to lower frequencies  
54 during static contractions is a valid and reliable measure of localised muscle fatigue <sup>8,9</sup>.  
55 However, neuromuscular changes in the sEMG signal are confounded by factors during  
56 dynamic movement such as variations in muscle length, muscle force output and contraction  
57 velocity <sup>8,10,11</sup>. Importantly, joint kinematics are directly related to relative displacement of the  
58 surface electrodes and the underlying muscle fibres, which affects the signal properties in  
59 both time and frequency domains <sup>10,12</sup>. Previous studies have demonstrated a relationship

60 between the variability of joint kinematics and the variability of the sEMG signal during  
61 dynamic movements<sup>12</sup>. Therefore, sEMG analysis of muscle activity during dynamic,  
62 functional movement should be preceded by kinematic investigation to identify potentially  
63 variable periods.

64

65 A strategy to reduce the variability in the sEMG signal during dynamic movement is to select  
66 the most mechanically reproducible portion of a repetitive movement<sup>12,13</sup>. If it is assumed  
67 that confounding mechanical variables remain invariant from trial to trial, then the spectral  
68 changes observed in the sEMG signal can be related to physiological processes<sup>12</sup>. While this  
69 strategy has been successfully demonstrated during lifting<sup>13-15</sup>, there is little information on  
70 the variability of hip and knee kinematics during a stepping task. Hip and knee kinematics  
71 reflect knee extensor and flexor muscle length and contraction velocity, therefore a detailed  
72 kinematic analysis should precede any attempt to validate stepping as a functional fatigue  
73 model to identify periods of the movement that may be highly variable and thus unsuitable for  
74 sEMG analysis. The aims of this study therefore, were threefold: Firstly, describe the  
75 kinematics of the knee and hip during a repetitive stepping task. Secondly, identify the period  
76 of peak inter-trial variability of hip and knee kinematics during step ascent and descent.  
77 Thirdly, assess the within-session reliability of hip and knee kinematics during repetitive  
78 stepping.

79

## 80 **Methods**

### 81 *Subjects*

82 A sample of convenience comprising 15 healthy males (age: 20.7±2.5 yrs; height: 1.78±0.05  
83 m; weight: 72.6±9.0 kg) were recruited from the university population to participate in the  
84 study. Males aged between 18-25yrs were tested to minimize age and gender effects on

85 movement kinematics. All subjects participated in recreational sport at least twice a week.  
86 They were asked to avoid intense exercise the day prior to each test session and on test days.  
87 None of the participants were familiar with the stepping exercise prior to the experiment.  
88 Each volunteer indicated that they were unaffected by any musculoskeletal or neurological  
89 conditions that may have impaired their ability to perform the experimental tasks. The QUT  
90 Human Research Ethics Committee granted ethical approval for this study and written  
91 informed consent was obtained prior to testing.

92

### 93 *Study Design*

94 This study was a part of a larger experiment to compare the efficacy and reliability of  
95 repetitive stepping and isokinetic exercise to induce muscle fatigue in the knee extensors. The  
96 experiment comprised of a test-retest cross-over study design, with each participant  
97 performing each fatigue protocol twice on separate days for a total of four test sessions (2  
98 protocols X 2 tests). The sessions were conducted at the same time of the day in randomised  
99 order, with a minimum separation of 14 days between each test.

100

### 101 *Data Collection*

102 The stepping protocol was performed in the motion analysis laboratory of the Institute of  
103 Health and Biomedical Innovation, QUT. Prior to the start of the test, reflective markers  
104 (10mm) were placed in a modified lower-limb Helen Hayes marker set <sup>16</sup>. Markers were  
105 placed bilaterally on the anterior superior iliac spines, the lateral femoral epicondyle, lateral  
106 malleolus of the fibula, calcaneus, and head of the second metatarsal, as well as the mid-  
107 sacrum. Markers mounted on wands were secured with Velcro straps to mid-thighs and mid-  
108 calf bilaterally. Three-dimensional coordinates of the markers were collected with a 6-camera

109 system at 200Hz (VICON Motion Systems Ltd., Oxford, UK). Kinetic data was collected at  
110 1000Hz with a force-plate (OR6-2000, AMTI, USA) mounted on a frame bolted to the floor  
111 of the laboratory (Figure 1). The contralateral foot made contact with forceplate mounted in  
112 the floor of the laboratory and a pressure-switch on the frame-mounted plate to identify the  
113 ascent and descent phases of the stepping movement while the lead foot remained stationary  
114 on the frame-mounted plate. Analog and video data were captured synchronously with motion  
115 capture software (VICON Motus 9.2, VICON Motion Systems Ltd., Oxford, UK) and stored  
116 on a computer.

117

118 The stepping protocol involved 50 stepping trials performed as rapidly as possible, while the  
119 participant wore a vest containing additional load equal to 10% of their bodyweight. A step  
120 trial involved the participant raising themselves to an upright standing posture on the frame  
121 (ascent) before returning their trailing limb to the floor-mounted force plate (descent). At the  
122 start of the test, the subject placed the leading test leg on the frame mounted platform matched  
123 to the height of the lateral tibial condyle (45 – 55cm high), with the contralateral leg placed  
124 shoulder width apart on the floor platform. All participants were tested with the right leg  
125 leading. The start and end postures were demonstrated to the subject prior to the  
126 commencement of each session to standardize the movements. Participants performed 10  
127 trials at a comfortable pace to familiarise themselves with the task. Participants were  
128 encouraged to attain a straight knee of the trail limb before the start of each stepping trial and  
129 a straight posture of both knees after ascent onto the frame (Figure 2). In addition, the lead  
130 foot was placed in a central point on the frame mounted platform in the anterior-posterior  
131 axis, offset to the right of the midline. The participant was asked to maintain this position of  
132 the leading leg, including contact with the platform throughout the test. Following the

133 familiarisation period, the participant performed the series of 50 step trials as fast as possible.

134 Arm position was not constrained during the experiment.

### 135 *Data Analysis*

136 A custom-written function in Matlab (version 2007a, Mathworks Inc. USA) split the stepping

137 movement into ascent and descent phases based on the data collected from the pressure switch

138 and the floor-mounted forceplate. The beginning of the ascent phase was defined as the point

139 at which the trail limb left the floor-mounted forceplate minus an offset. The offset was

140 calculated as the average time between the trail foot impact at the end of the descent and the

141 foot leaving the plate to ascend the platform. The end of the ascent phase was defined as the

142 point at which the trail limb contacted the pressure-switch mounted on the forceplate mounted

143 on the platform. The descent phase was defined as the period between the foot leaving the

144 pressure-switch and contacting the floor forceplate.

145

146 Hip and knee flexion displacement and velocity were calculated during ascent and descent

147 phases using established equations<sup>16</sup>. The data were first resampled to 1000Hz using a quintic

148 spline processor for synchronization with the analog data. Following phase identification,

149 each data vector was then interpolated to a length of 100 points using a fast Fourier transform

150 (FFT) interpolation function<sup>17</sup>. Key variables extracted from each phase (ascent and decent)

151 were maximum and minimum flexion angles, range of motion and timing of maximum joint

152 flexion. The magnitude and timing of peak velocity in flexion and extension were determined.

153 All timings were expressed as % of the phase duration.

154

### 155 *Statistical Analysis*

156 Data was assessed for normality and equality of variance prior to further analysis. Data from

157 the 50 stepping trials were grouped evenly into 10 blocks of 5 trials, with inter-trial variability

158 of angular displacement and velocity calculated over each 5-trial block with root mean square  
159 error (RMSE). Inter-joint differences in kinematics were assessed at trial block 1 and trial  
160 block 10 with Mann-Whitney U tests. Ten RMSE vectors were calculated for each variable  
161 for each participant, for the ascent and descent phases of stepping. Calculating the error  
162 relative to the mean of each trial block accounted for any changes in kinematic parameters  
163 across the 50-trial test. Kruskal-wallis ANOVA with Dunn-Sidak post-hoc comparisons to  
164 assess within-session changes in angular displacement and velocity across trial blocks (Blocks  
165 1-10). Significance level was set a-priori at  $P < 0.05$  for all statistical tests, which were  
166 performed in Minitab (version 16, Minitab Inc, MA, USA). Linear changes in kinematic  
167 variables between trial blocks were quantified with linear regression in Microsoft Excel  
168 (v2010).

169

## 170 **Results**

171 All subjects successfully completed both sessions of 50 stepping trials. Angular displacements  
172 of the hip and knee were similar and both demonstrated a pattern of flexion-extension during  
173 ascent and the reverse during descent (Figure 3). During the first block of trials, the hip and  
174 knee moved through similar ( $P = 0.097$ ) ranges of motion and finished the movement with  
175 similar minimum flexion angles during step ascent (Table 1). In contrast, peak flexion  
176 velocity of the knee during ascent was significantly ( $P < 0.01$ ) higher than the hip, while no  
177 significant difference was observed for peak extension velocity (Table 1). The peak flexion  
178 velocity of the knee during descent was significantly greater ( $P < 0.01$ ) and occurred later in  
179 the movement than the hip (Table 1). Inter-joint differences in kinematics remained during the  
180 last blocks of trials (Table 2). However, the peak extension velocity of the knee during ascent  
181 was significantly greater than the hip during the last trial block, although no difference was  
182 detected during the first trial block.



183

184 Inter-trial variability of angular velocity peaked for both joints between 21 and 40% of the  
185 ascent (Figure 3 – top). Knee velocity variability at 21-40% of the ascent was significantly  
186 higher than all other sub-phases except 81-100%, while the hip was significantly higher  
187 during this sub-phase compared to 41-100% (Figure 4 - top). Importantly, the inter-quartile  
188 range was substantially larger during 21-40% than any other part of the ascent. During  
189 descent, significant differences were observed between RMSE at 0-20% of the movement,  
190 compared to all other sub-phases for both joints. In addition, RMSE during 81-100% of the  
191 descent was also significantly ( $p>0.05$ ) different to the remaining sub-phases (Figure 4 –  
192 bottom).

193

194 Hip and knee kinematics did not remain stable across the 10 blocks of trials. Joint range of  
195 motion significantly decreased from the first trial block to the last (Figure 5 – top), which was  
196 explained by a concomitant increase in the minimum flexion angle (Figure 5 – bottom).  
197 Linear regression revealed a reduction in range of motion of  $1.8^\circ$  and  $1.4^\circ$  per trial-block for  
198 the hip and knee respectively (Figure 5). While peak knee flexion velocity during ascent  
199 increased significantly across trial blocks, peak hip flexion velocity remained unchanged  
200 (Figure 6 – top). These changes equated to an average peak flexion velocity increase of  $4.5^\circ/s$   
201 per trial block. A contrasting pattern was observed for peak extension velocity, with the hip  
202 decreasing significantly across trial blocks ( $3.9^\circ/s$  per trial block) and the knee unchanged  
203 (Figure 6 – bottom). Peak knee flexion velocity increased linearly during step descent (Figure  
204 7 – top) at  $6.5^\circ/s$  per trial-block, although hip flexion velocity remained constant. The timing  
205 of peak knee flexion velocity also increased during descent (Figure 7 – bottom), while peak  
206 hip flexion velocity displayed fewer significant differences between trial-blocks.

207

## 208 **Discussion**

209 The first aim of this study was to describe the kinematics of the knee and hip during a  
210 repetitive stepping task. On average, healthy young men employed a pattern of hip-knee  
211 flexion followed by rapid extension to ascend the knee-high step and a reverse pattern to  
212 descend the step. While this is the first study to report hip and knee kinematics with such a  
213 high step rise (~50cm), the angular displacements observed were comparable to previous  
214 studies at lower step heights (18cm)<sup>18,19</sup>. The flexion-extension joint motion during step  
215 ascent may reflect the participants' attempts to take advantage of the stretch-shorten cycle to  
216 generate adequate joint power<sup>20</sup>. That is, initial stretching of the hip and knee extensors  
217 during joint flexion enhance the mechanical output of the proceeding concentric muscle  
218 contraction as the hip and knee extend during step ascent. However, inter-joint differences in  
219 peak joint velocity and peak joint velocity timing revealed a more complex movement pattern  
220 than initially thought. These complex patterns may be explained by the energy requirements  
221 of raising and lowering the body's centre of mass during the stepping motion<sup>21</sup>, which may  
222 require redistribution of forces between the hip and knee extensors<sup>22</sup>. The kinematics  
223 observed are more complicated than the pure joint extension during ascent and flexion during  
224 descent that would be assumed to occur. Future studies should consider partitioning the ascent  
225 and descent phases of the stepping movement into sub-phases representing eccentric and  
226 concentric muscle actions.

227

228 The second aim of the study was to identify the period of peak inter-trial variability of hip and  
229 knee kinematics during step ascent and descent. Inter-trial variation in joint kinematics has  
230 important implications for sEMG of the hip and knee extensors during stepping. In particular,  
231 sEMG signal analysis can be confounded by changes in movement biomechanics (non-  
232 physiological factors), which interfere with the observation of physiological processes, such

233 as muscle fatigue (De Luca, 1997). Strategies to minimise confounding by variations in joint  
234 kinematics have been proposed which involve selecting the most mechanically reproducible  
235 part of a cyclic movement<sup>12</sup>. The presence of a stretch-shorten pattern during both phases of  
236 the stepping trial produced spikes in inter-trial variation of joint velocity coinciding with the  
237 transition from flexion to extension. Hip and knee angular velocity RMSE nearly doubled  
238 during the transition periods compared to the rest of the movement phase. This can be  
239 attributed to variations in the timing of the transition between trials. That is, differences in  
240 timing of as little as 1% between trials would mean that positive (flexion) velocities were  
241 averaged with negative (extension) joint velocities. Therefore, future studies that conduct  
242 sEMG of functional protocols should proceed with caution when attempting to analyse signals  
243 collected from 21-40% of the step ascent and 81-100% of the descent, where flexion-  
244 extension transitions occur.

245

246 The third aim of the present study was to assess the within-session reliability of hip and knee  
247 kinematics during repetitive stepping. A key finding was that angular displacement and peak  
248 joint velocity did not remain stable across the 50-trial test. Such a result is not unexpected  
249 considering the fatiguing nature of the task, with reductions in joint range of motion, peak hip  
250 extension velocity and increased peak knee extension velocity possibly reflecting adaptation  
251 strategies to maintain maximum movement speed across the 50 trials<sup>23,24</sup>. However, these  
252 alterations may confound future sEMG analyses if stepping is to be used a functional fatigue  
253 model of the hip and knee extensors. In particular, estimates of sEMG signal frequency may  
254 be influenced by the changes in joint angle during ascent, as well as alterations in joint  
255 velocity during ascent and descent<sup>10,11</sup>. Knee kinematics are influenced by external  
256 constraints<sup>25</sup>, with improved within-session reliability of knee kinematics during constrained  
257 squats compared to free squats and wall slides<sup>26</sup>. These findings have important implications

258 for future studies intending to use repetitive stepping as a fatigue model for the knee extensors  
259 and flexors, which may rely on surface EMG. Therefore future work may be required to  
260 constrain hip and knee motion with mechanical devices rather than verbal encouragement to  
261 improve reliability, as well as develop algorithms to adjust the sEMG analysis to compensate  
262 for changes in joint range of motion and velocity.

263

264 As with any study of this kind, the results should be interpreted in the context of its  
265 limitations. Firstly, the analysis was impeded by considerable between-participant variation of  
266 hip and knee kinematics, which is reflected in the inter-quartile ranges of the results (Figures  
267 4 - 7). Study recruitment was restricted to a narrow age range of university males to minimize  
268 gender and age effects and attempts were made to standardize the stepping task for each  
269 participant, such as matching the step height to the tibial tuberosity, standardizing placement  
270 of the lead foot on the step, implementing familiarization trials and verbally encouraging the  
271 participant to attain standard postures. Despite these measures, the sample displayed  
272 considerable between-participant variability in hip and knee kinematics, which is a recognized  
273 characteristic of human movement <sup>27</sup>, but also encourages the need for caution when  
274 interpreting the group results. The second limitation of the present study was the restriction of  
275 the analysis to the sagittal plane, with potential implications for sEMG analysis with respect  
276 to the secondary axes of motion at both joints. Previous work has illustrated that constraining  
277 lower limb posture with mechanical means can also improve tibial rotation reliability during  
278 squats <sup>26</sup>. These findings provide opportunities to plan and execute dynamic sEMG analysis of  
279 functional, cyclical lower-limb movements to study muscle function.

280

281

282 **Conclusions**

283 The hip and knee undergo complex patterns of sagittal motion to ascend and descend a knee-  
284 high step. Transitions between flexion-extension for the knee and hip during step ascent and  
285 descent coincide with periods of high inter-trial variability of joint kinematics which should  
286 be avoided in future sEMG analyses. Furthermore, hip and knee kinematics do not remain  
287 stable during a repetitive stepping task, possibly due to compensation strategies, which may  
288 further confound attempts to monitor muscle function. Future work should endeavor to  
289 constrain lower limb knee motion within the context of a functional lower-limb task to  
290 improve the reliability of sEMG data, as well as develop algorithms to adjust the signal to  
291 account for biomechanical variations within and between participants.

292

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376

377 **Tables**

378

379

380 Table 1: Hip and knee kinematics (median and inter-quartile ranges) with inter-joint

381 differences during Trial Block 1 of the repetitive stepping task

382

	<b>Hip</b>	<b>Knee</b>	<b>P-value</b>
<b>Ascent</b>			
Range of motion	67.7 (63.3 – 78.3)	73.4 (68.5 – 77.7)	0.097
Minimum Joint Angle	22.1 (11.4 – 26.5)	16.2 (11.6 – 20.9)	0.097
Peak Flexion Velocity	164.2 (142.6 – 205.5)	251.2 (227.9 – 276.6)	<0.01
Peak extension velocity	225.2 (206.9 – 272.6)	254.8 (237 – 292.3)	0.051
<b>Descent</b>			
Peak Flexion Velocity	203.4 (190.2 – 212.7)	246.2 (226.7 – 276.9)	<0.01
Peak Flexion Velocity Timing (%)	70 (62-83)	84 (74-87)	0.049

383

384 Table 2: Hip and knee kinematics (median and inter-quartile ranges) with inter-joint

385 differences during Trial Block 10 of the repetitive stepping task

386

	<b>Hip</b>	<b>Knee</b>	<b>P-value</b>
<b>Ascent</b>			
Range of motion	52.3 (46.5 – 75.7)	60 (53.3 – 67.8)	0.41
Minimum Joint Angle	37.4 (14.3 – 43.4)	29.6 (22.0 – 36.6)	0.36
Peak Flexion Velocity	175.2 (153.1 – 187.6)	288 (277 – 315.3)	<0.01
Peak extension velocity	193.4 (167 – 234.7)	276.7 (259.1 – 310.7)	<0.01
<b>Descent</b>			
Peak Flexion Velocity	209.8 (183.5 – 254.7)	304.7 (250.4 – 322.7)	<0.01
Peak Flexion Velocity Timing	82 (72 – 87)	86 (85 – 90)	0.018

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389



390 **Figures and Captions**

391



392

393

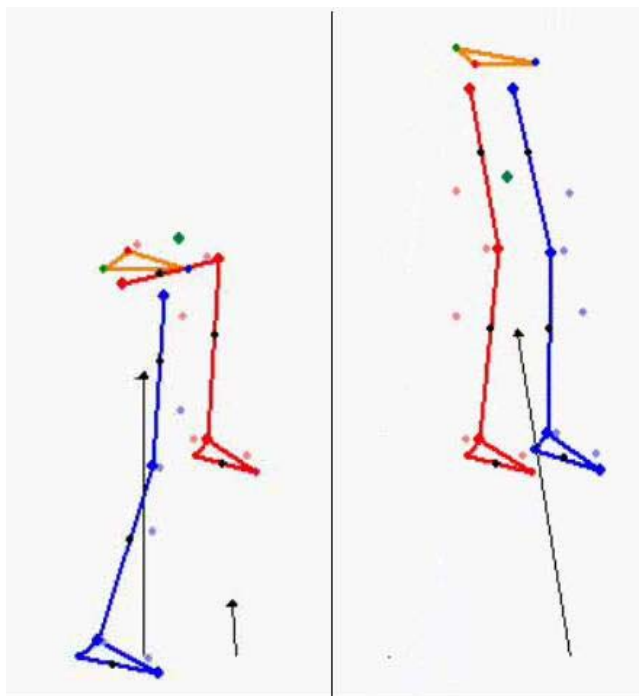
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Figure 1: Forceplate fixed to a frame to provide a stepping platform for the repetitive stepping task. Note the pressure switch on the top of the platform with battery pack attached with red wire (left side of frame)



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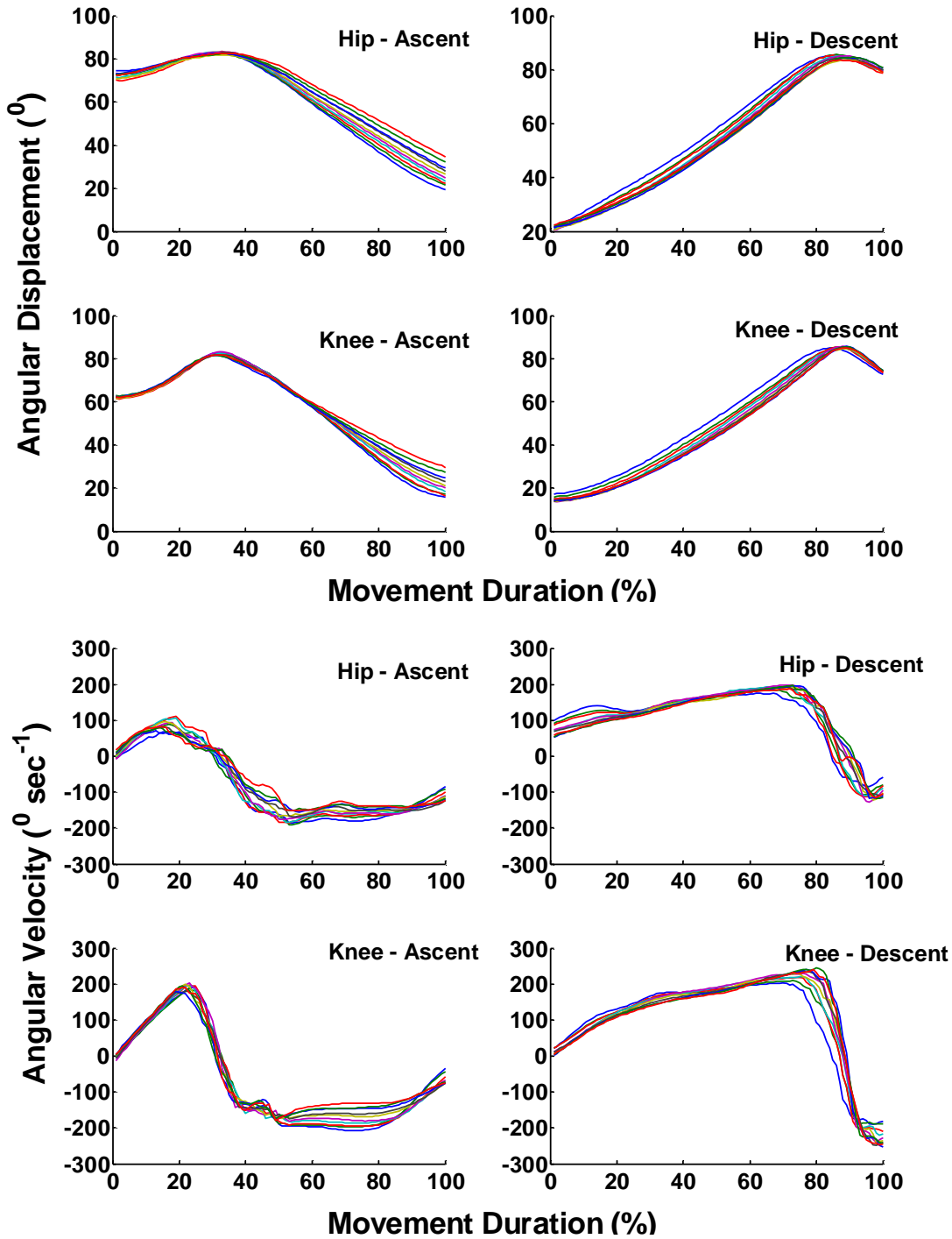
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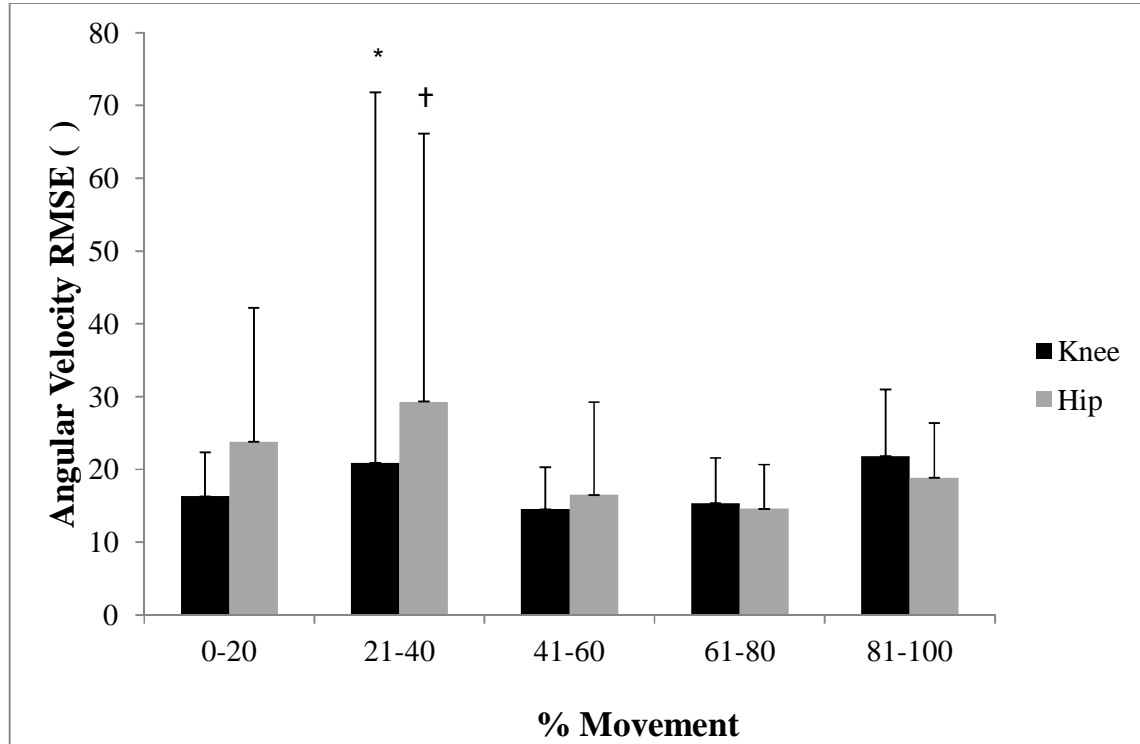
Figure 2: Key postures of the stepping trial illustrated with ground reaction force vectors. The end position of the ascent movement (right) was also the starting position for the step-down movement



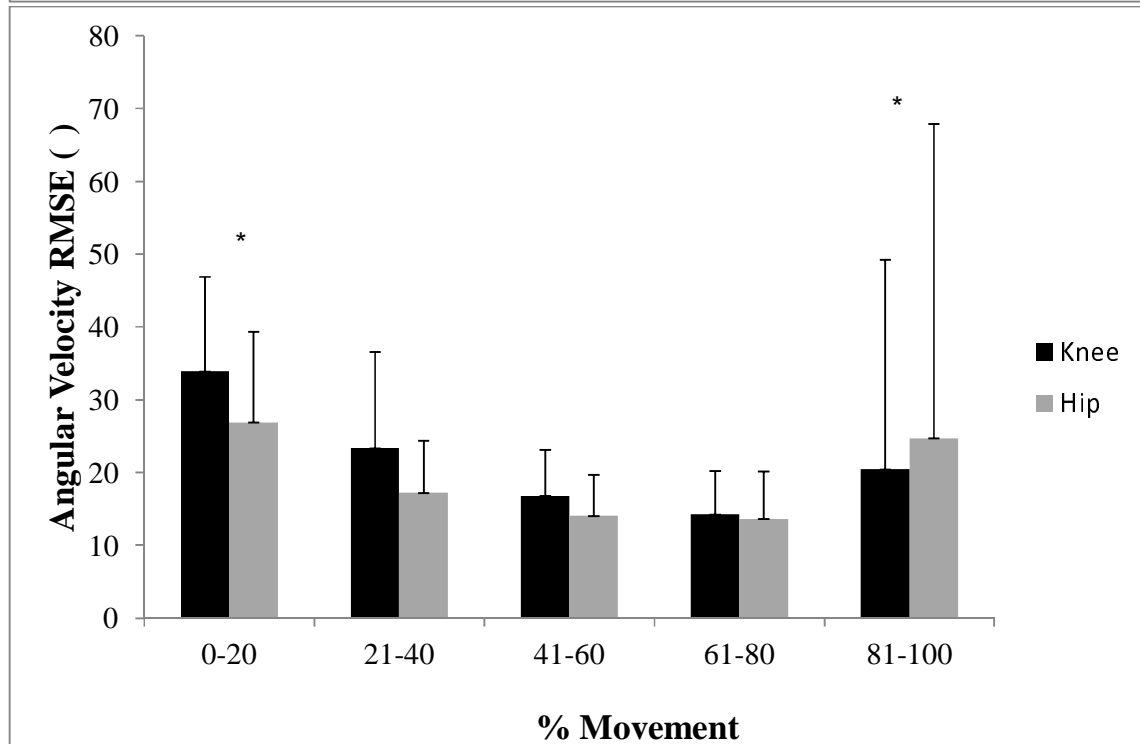
408 Figure 3. Average angular displacement (top) and angular velocity (bottom) curves across  
409 trial blocks (10) for the hip and knee during the ascent and descent phases of the repetitive  
410 stepping movement  
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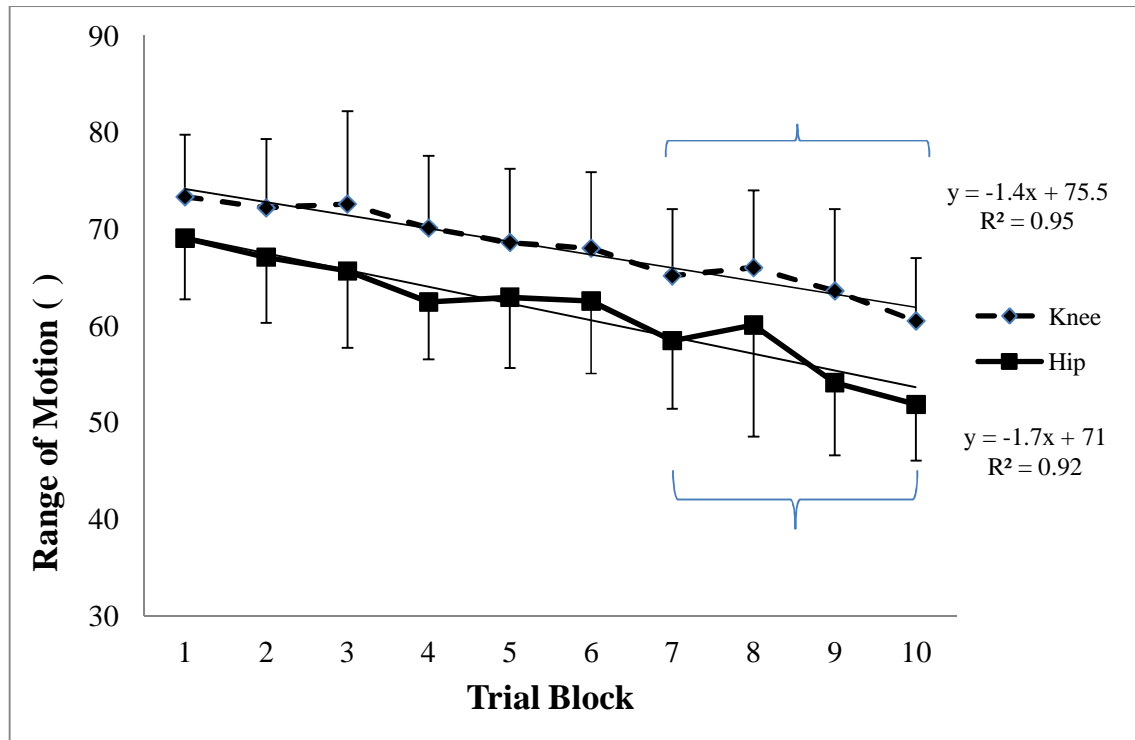
417 Figure 4. Inter-trial variability of angular velocity for the hip and knee compared across sub-

418 phases during the ascent (top) and descent (bottom) of the stepping movement. \* significantly

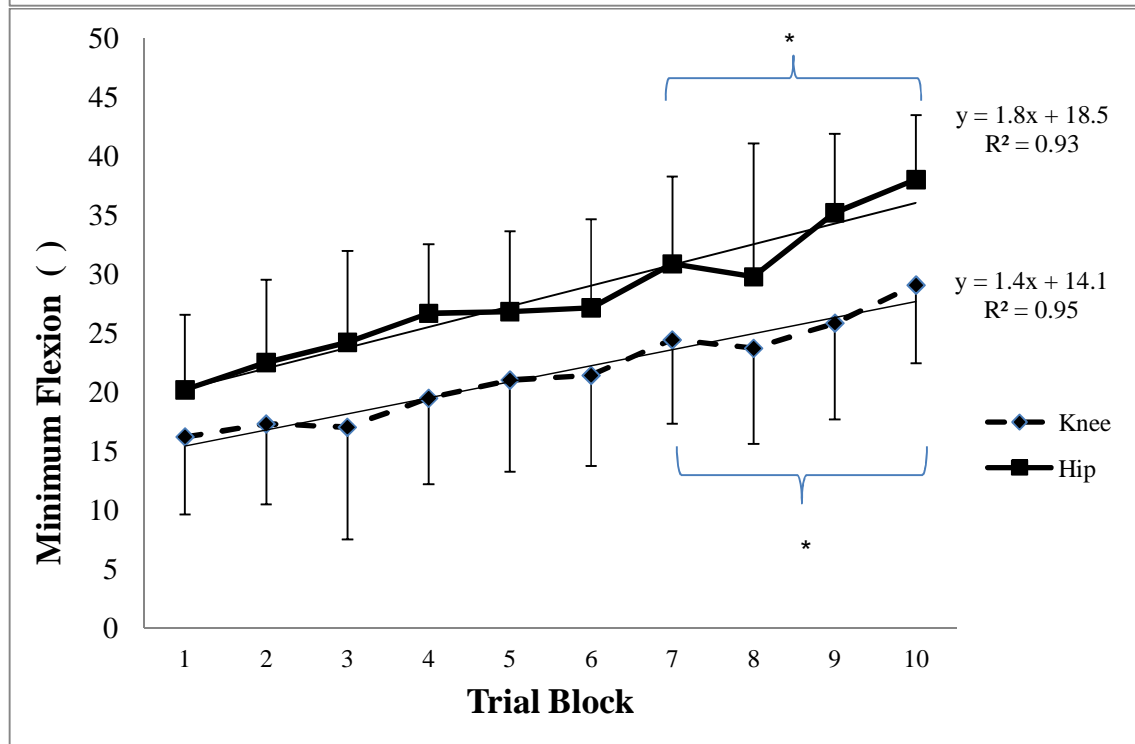
419 ( $p < 0.05$ ) different to all other sub-phases. † significantly different to 41-100%

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425 Figure 5. Within-test variation of angular displacement during step-up. Changes in range of

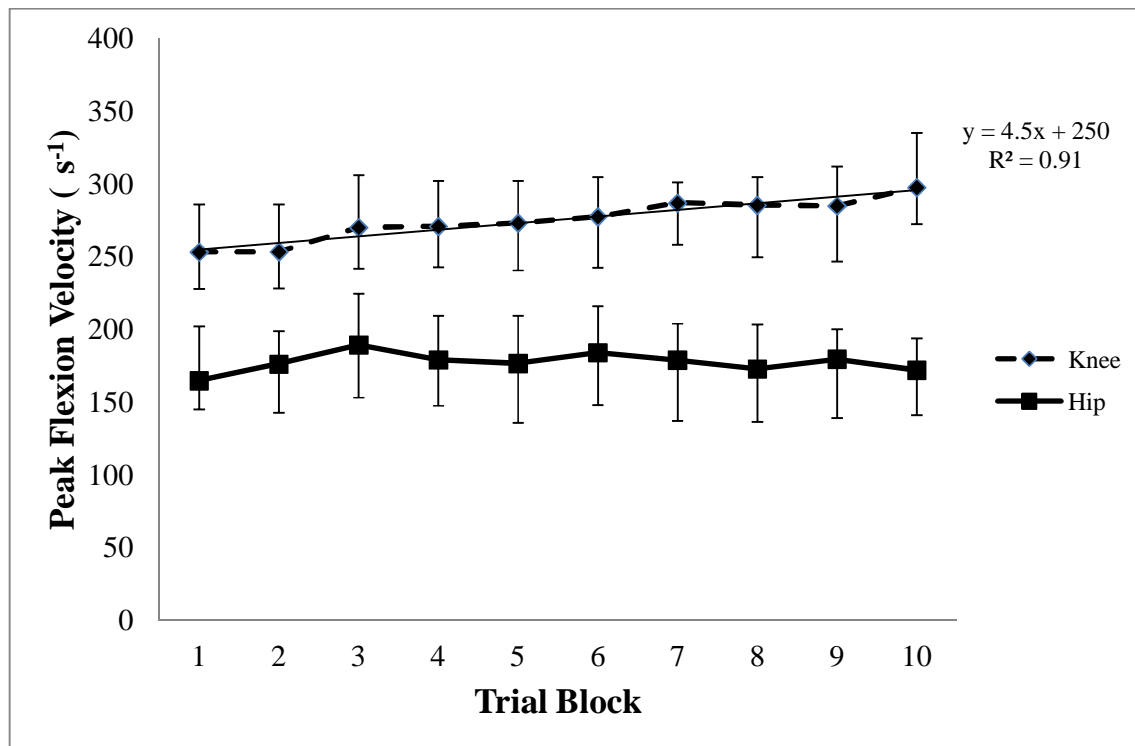
426 motion (top) and minimum flexion (bottom) across trial blocks. Data represented by

427 median±inter-quartile range. \*significantly different (p<0.05) to blocks 1-3

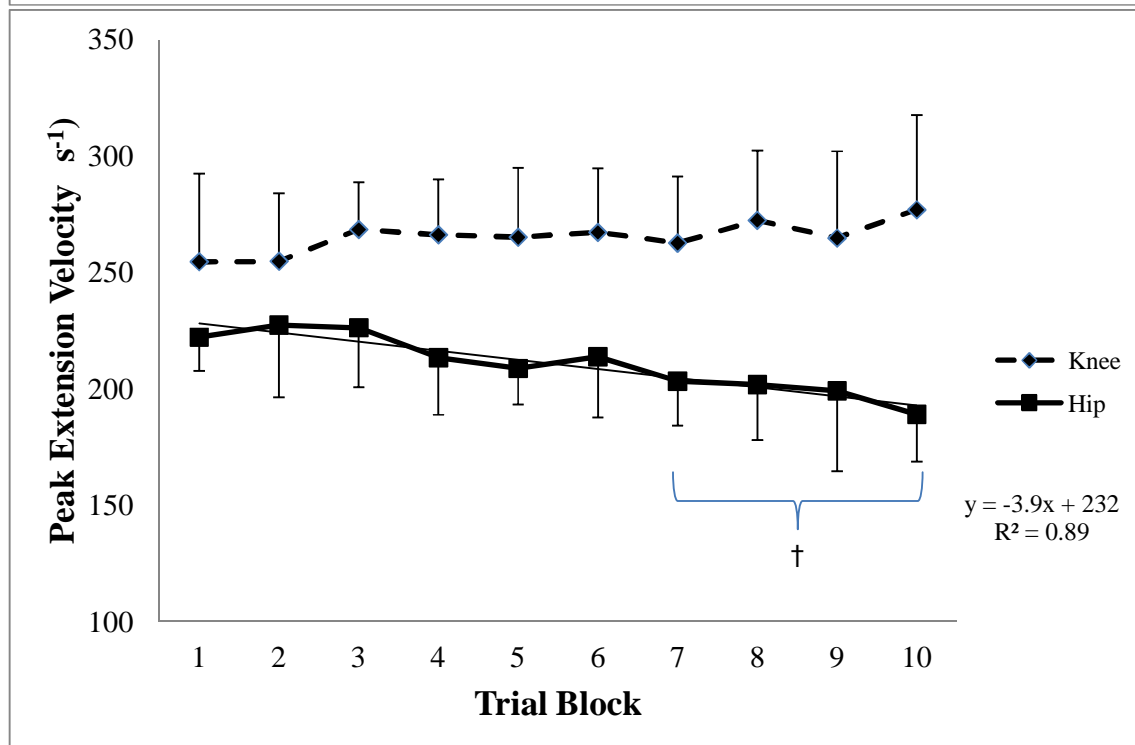
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Figure 6. Within-test variation during step ascent of peak flexion velocity (top) and peak extension velocity (bottom) across trial blocks. Data represented by median±IQR. \* significantly different ( $p < 0.05$ ) to trial blocks 1 and 2 † significantly different to trial blocks 1-3

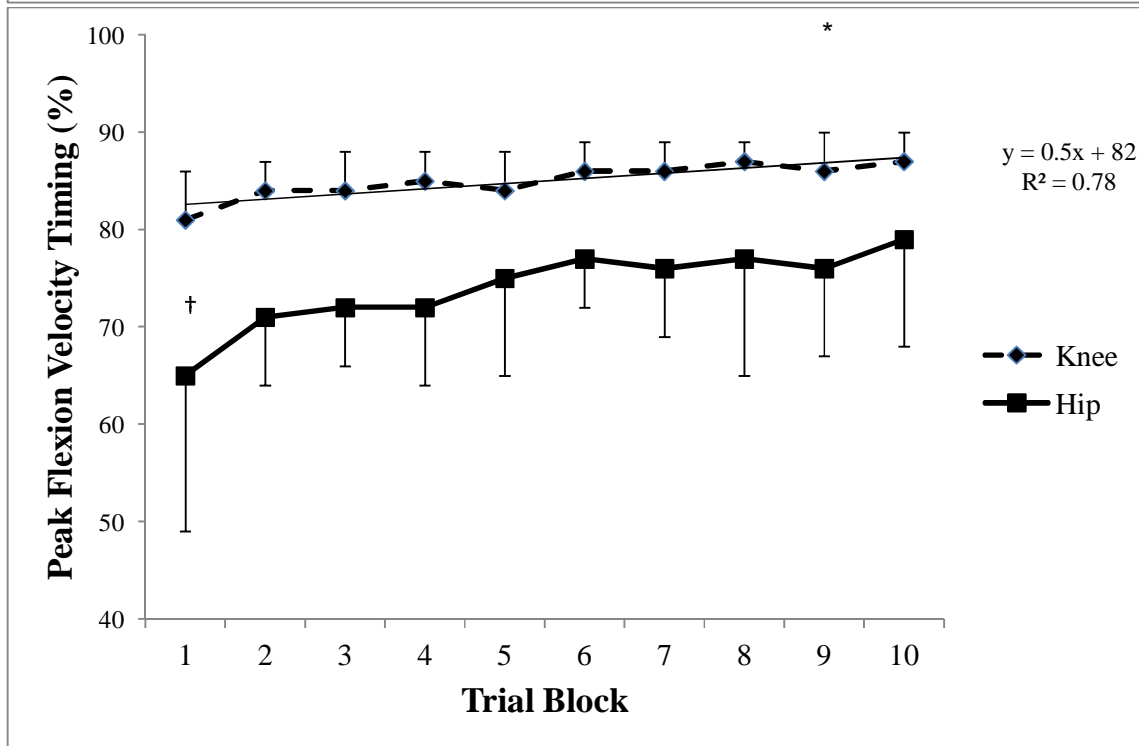
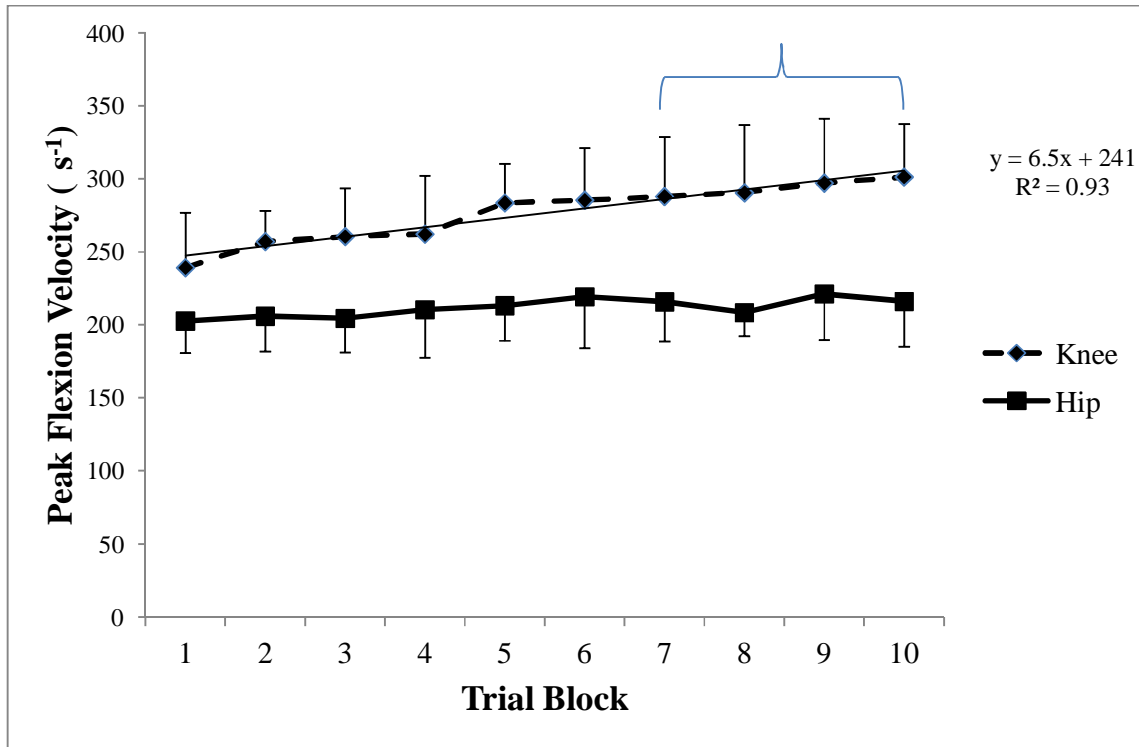


Figure 7. Within-test variation during step descent of peak flexion velocity (top) and time of peak flexion velocity (bottom) across trial blocks. Data represented by median±IQR  
\*significantly different (p<0.05) to blocks 1-3. † significantly different (p<0.05) to all other blocks