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Do lower-extremity joint dynamics change when stair negotiation is initiated with a self-selected comfortable gait speed?

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1 **Abstract**

2 Previous research on the biomechanics of stair negotiation has ignored the effect of the
3 approaching speed. We examined if initiating stair ascent with a comfortable self-selected speed
4 can affect the lower-extremity joint moments and powers as compared to initiating stair ascent
5 directly in front of the stairs. Healthy young adults ascended a custom-built staircase
6 instrumented with force platforms. Kinematics and kinetics data were collected simultaneously
7 for two conditions: starting from farther away and starting in front of the stairs and analyzed at
8 the first and second ipsilateral steps. Results showed that for the first step, participants produced
9 greater peak knee extensor moment, peak hip extensor and flexor moments and peak hip positive
10 power while starting from farther away. Also, for both the conditions combined, participants
11 generated lesser peak ankle plantiflexor, greater peak knee flexor moment, lesser peak ankle
12 negative power and greater peak hip negative power while encountering the first step. These
13 results identify the importance of the starting position in experiments dealing with biomechanics
14 of stair negotiation. Further, these findings have important implications for studying stair ascent
15 characteristics of other populations such as older adults.

16 **Keywords: stair ascent, joint moments, joint powers, stair negotiation, stair climbing**

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25 **Introduction**

26 Stair negotiation is a common activity of daily living that is challenging for certain
27 populations. More than two-thirds of people aged 65 or above experience falls every year [1,2,3]
28 and more than 10% of these falls have been attributed to stair negotiation [4,5]. It is estimated
29 that fall-related injuries resulted in 6% of all medical expenditures for older adults [6,7].
30 Therefore, there has been great research interest on the biomechanics of stair negotiation in order
31 to understand the mechanisms related with these falls.

32 Compared to level walking, stair ascent is characterized by large sagittal plane joint
33 moments and powers, particularly at the knee and ankle joints [8,9,10]. Also, stair ascent is
34 characterized by concentric muscle contraction and energy generation (positive muscle work).
35 The knee extensor muscles assisted by the ankle plantiflexors and the hip extensors generate
36 energy to help support and propel the body upward and forward [9]. Previous researchers have
37 found that during stair ascent all the joints produce energy during most of the stride [8,11]. Peak
38 knee and hip joint powers occur at the beginning and the peak ankle plantar flexion power occurs
39 at the end of the stance phase.

40 Interestingly, in previous research ascent was initiated exclusively directly in front of the
41 stairway [9,10,11,12,13]. However, initiating stair ascent farther away from the stairs could
42 allow participants to achieve a more natural gait speed before the transition phase from level
43 walking to stepping on the stairway. This is actually the case many times when we negotiate
44 stairs (for example at home or in a mall). Initiating stair ascent in front of the stairway would
45 probably require more energy generation than initiating from farther away. This might influence
46 magnitudes of both joint moments and powers. However, this information is currently unknown.
47 Therefore, the objective was to address this knowledge gap and determine how different are the

48 joint moments and powers when one begins stair ascent after achieving a comfortable gait speed
49 compared to beginning stair ascent from a static position directly in front of the stairs. We
50 hypothesized that the joint moments and powers during stair negotiation will be different
51 between the two conditions. Additionally, these differences will appear in consecutive ipsilateral
52 footfalls on the stairs.

53 **Methods**

54 Ten healthy young adults (3 females; 26.4 ± 3.7 years; 76.2 ± 13.6 kg; 1.78 ± 0.08 m) gave
55 their consent approved by the local institutional review board to participate in the study.
56 Inclusion criteria were: age between 19-35 years and free of any injury that could impair
57 walking. Exclusion criteria were: presence of any known sensory, neuromuscular, skeletal or
58 cardiovascular disorders that may affect a gait or the inability to negotiate stairs used in the study
59 without using handrails.

60 Kinematic data were collected at 60 Hz using eight digital cameras (Motion Analysis
61 System, Santa Rosa, CA). Kinetic data were collected at 600 Hz using two AMTI (Advanced
62 Mechanical Technology Inc., Watertown, MA) force platforms embedded in the first and the
63 third stair treads. This instrumented stairway consisted of four steps with step rise of 18 cm, step
64 width of 46 cm, step tread of 28 cm and angle of stairway rise of 32.73° (Figure 1). The
65 dimensions of the staircase were selected because they are among the most frequently
66 encountered and are within the recommended stair dimensions by the Occupational Safety and
67 Health Standards [14,15].

68 Participants wore a tight-fitting suit and retro-reflective markers were placed on their
69 pelvis and lower limbs based on modified Helen Hayes marker set [16]. All the participants were
70 allowed to practice before testing. Also, in order to reduce the risk of falling while ascending the

71 stairs, they were instructed to use the handrails if needed. However there were no trials involving
72 a loss of balance or grabbing the handrails.

73 Photo cells positioned in front of the stairway were used to determine the self-selected
74 speed for the approach of stair ascent (Figure 1). Participants were instructed to walk towards the
75 stairs at their self-selected comfortable speed from a distance of 5 m and their speed was
76 calculated based on the time recordings of the photocells placed 2 m apart. An average walking
77 speed from 16 trials was deemed as the self-selected comfortable speed for each participant.
78 Next, the participants were asked to perform two stair ascent conditions, starting with the right
79 limb for each condition: 1) Farther: stair ascent starting farther away from the stairway
80 (condition 1; Figure 1), and 2) Front: stair ascent starting in front of the stairway (condition 2;
81 Figure 1). An acceptable trial for the condition when starting farther away from the stairway
82 needed the participant to ascend the stairway within $\pm 10\%$ of the determined self-selected
83 comfortable speed. The order of the conditions was randomized.

84 These variables were selected according to the literature [8,17,18] and were calculated for
85 both the first and second steps of the right limb on the staircase during both conditions (Table 1).
86 For each condition five trials were averaged for each subject and the mean maximum and
87 minimum joint moments and powers as defined above were calculated. These values were then
88 averaged to provide the group means and standard deviations. Calculation of joint moments and
89 powers was accomplished using a custom-made Matlab (Mathworks Inc., Natick, MA) program.

90 A repeated 2x2 ANOVA was performed. The factors were a) two consecutive footfalls on
91 the stairway with the right limb (Steps 1 and 2; Figure 1) and b) two initial speed conditions of
92 stair ascent (starting farther away from the stairway and starting in front of the stairway). The

93 statistical analysis was performed using the SPSS software (SPSS Inc., Chicago, IL). The α -
94 value was set at 0.05.

95 **Results**

96 The ANOVA results revealed a significant step main effect ($P=0.031$) for peak
97 plantiflexor moment with a 7% greater value during the second step (Table 1; Figure 2). There
98 was no significant initial speed main effect ($P=0.543$) or a significant interaction ($P=0.108$).
99 Further, for the peak dorsiflexor moment no significant differences were found for the main
100 effects of initial speed ($P=0.549$) and step ($P=0.179$) and for the interaction ($P=0.694$). Overall,
101 initial speed had minimal effect on the ankle joint moments whereas the higher step needed
102 participants to exert greater peak plantiflexor moment prior to foot-off.

103 The ANOVA results for the peak knee extensor moment showed a significant initial
104 speed main effect ($P=0.047$) but no step main effect ($P=0.502$). The peak knee extensor moment
105 following foot-strike was 10% greater when the participants ascended the stairs starting from
106 farther away (Table 1; Figure 2). Additionally, a significant interaction was also noted
107 ($P=0.010$). When the participants initiated stair ascent starting from farther away, the peak knee
108 extensor moment decreased for the second step by 21%. Conversely, when starting from up
109 front, participants generated 3% greater peak knee extensor moment following foot-strike on the
110 second step (Figure 4A). For the peak knee flexor joint moment prior to toe-off, the ANOVA
111 results showed a significant step main effect ($P=0.001$) with a 62% greater moment during the
112 first step (Table 1; Figure 2). No significant initial speed main effect ($P=0.454$) and interaction
113 were observed ($P=0.361$) for the peak knee flexor moment.

114 For the peak hip extensor moment, the ANOVA results revealed a significant initial
115 speed main effect ($P=0.005$) with the participants producing a 10% greater moment while

116 ascending the stairs starting farther away (Table 1; Figure 2). However no significant step main
117 effect ($P=0.568$) or interaction ($P=0.500$) were noted. For the peak hip flexor moment, a
118 significant initial speed main effect ($P=0.016$) was observed where the moment was 16.5%
119 greater when the participants ascended the stairs starting farther away (Table 1; Figure 2). There
120 was no significant step main effect ($P=0.308$). A significant interaction ($P=0.029$) showed that
121 when the participants started from farther away, the peak hip flexor moment decreased
122 minimally (by 5%) from the first step to the second step. However, when stair ascent was
123 initiated from in front of the stairs, the peak hip flexor moment increased (by 19%) from the first
124 step to the second step (Figure 4B).

125 The ANOVA results showed a significant step main effect for peak ankle negative power
126 ($P=0.043$) with a 41% greater rate of energy absorption on the second step (Table 1; Figure 3).
127 There was no significant initial speed main effect ($P=0.702$) or interaction ($P=0.839$). For the
128 peak positive power before toe-off, no significant main effects for step ($P=0.588$) and for initial
129 speed ($P=0.795$) were noted. However, a significant interaction ($P=0.015$) was observed. When
130 the participants started from farther away, they produced more 8% positive power on the second
131 step. But when the participants started in front of the stairs, they produced 2% less positive
132 power on the second step (Figure 4C).

133 Though significant main effects for step ($P=0.174$) and for initial speed ($P=0.737$) were
134 absent, the ANOVA results indicated a significant interaction for the peak knee positive power
135 ($P=0.030$). The amount of peak knee positive power after foot-strike was similar between both
136 steps when the participants started farther away from the stairs. But, when they started in front of
137 the stairs, the amount of knee positive power decreased from the first step to second step by 15%
138 (Figure 4D).

139 The ANOVA results for peak positive power during hip extension immediately after foot-
140 strike exhibited significant main effects for step ($P=0.006$) and initial speed ($P=0.050$).
141 Participants produced 34% more peak positive power while ascending the second step and 14%
142 more peak positive power starting from farther away (Table 1; Figure 3). No significant
143 interaction was observed ($P=0.099$). For the peak negative power at the hip, a significant step
144 main effect was noted ($P=0.006$) with 29% greater peak negative power while ascending the first
145 step (Table 1; Figure 3). However there were no significant initial speed main effect ($P=0.360$)
146 and interaction ($P=0.535$).

147 **Discussion**

148 The primary objective of this study was to determine the differences in the joint moments
149 and powers when one begins stair ascent after achieving a comfortable gait speed compared to
150 beginning stair ascent from a static position directly in front of the stairs. Our first hypothesis
151 was that the joint moments and powers during stair negotiation will be different between the two
152 conditions. Our second hypothesis was that these differences will also appear in consecutive
153 ipsilateral footfalls on the stairs. Collectively, our results supported both hypotheses.

154 The first hypothesis was supported by the ankle joint results in terms of the peak positive
155 power before toe-off. When the participants started from farther away, the peak positive ankle
156 power before toe-off at the first step was lesser compared to starting from in front of the stairs.
157 This could be due to the fact that the gait speed prior to stepping on stairs allows one to move
158 forward with additional momentum relying less at the ankle positive power to ascend the stairs.
159 Further, the effect of the gait speed seemed to diminish on the second step where the participants
160 needed greater peak ankle positive power to ascend further up. These observations also echoed
161 for the peak plantiflexor moment before toe-off though no significant results were noted. The

162 curve profiles from Figure 2 suggest that on the first step, participants seemed to generate lesser
163 peak plantiflexor moment before toe-off when starting farther away from the stairs. Differences
164 between both the conditions could also be spotted in Figure 2, in terms of lesser peak plantar
165 flexion after foot-strike and greater peak dorsiflexion for stair ascent starting from afar.
166 Nonetheless, no such characteristic distinctions between the conditions could be seen for the
167 second step. The first hypothesis was also supported for the knee joint in terms of the peak knee
168 extensor moment and the peak knee positive power following foot-strike. Particularly, the peak
169 knee extensor moment was greater on the first step while ascending stairs starting farther away.
170 At foot-strike, stair ascent demands more knee flexion compared to level-walking. Perhaps the
171 participants generated a greater knee extensor moment to compensate for the change from level-
172 walking to stairs. However, they did not have to worry about this factor while ascending from the
173 front of the stairs. Also, once stair ascent was initiated, the difference in the peak knee extensor
174 moment generated in both the conditions minimized at the second step.

175 The peak knee positive power at foot-strike decreased from the first step to the second
176 step when the participants started from the front of the stairs. However when the participants
177 started from farther away, this peak knee positive power remained relatively constant between
178 the two steps. Comparisons between the peak knee joint positive power during extension and
179 peak knee joint extensor moment could highlight the differences in the action of the quadriceps.
180 For the condition of starting farther away, the quadriceps had to produce greater peak knee joint
181 moment but lesser peak knee positive power at the first step. This could be due to a greater knee
182 angular velocity while approaching stair ascent with a gait speed. The first hypothesis for the hip
183 joint was also supported in terms of the peak hip extensor and flexor moments and the peak hip
184 positive power. The curve profiles in Figure 2 indicated greater peak hip extensor and flexor

185 moments when the participants started farther away, probably indicating the overall effect of gait
186 speed on hip joint dynamics. Also, greater peak hip extensor moment would have translated to
187 greater peak hip positive power by the hip extensors at foot-strike when the participants initiated
188 stair ascent from farther away. The peak hip flexor moment showed characteristics similar to the
189 peak knee extensor moment discussed above. The hip flexors probably generated greater hip
190 flexor moment during toe-off at the first step while starting from afar due to the stair gait speed.
191 However, the differences between the conditions were minimized at the second step due to
192 change in stair gait speed during toe-off at the second step. Combined, these observations
193 revealed that when participants ascended the stairs from farther away, the hip and knee extensors
194 generated greater peak extensor moments and positive powers following foot-strike.

195 The second hypothesis was supported at the ankle joint in terms of greater peak negative
196 power following foot-strike and greater peak plantiflexor moment before ipsilateral toe-off on
197 the second step. Greater and faster muscle activation of the soleus and gastrocnemius while
198 climbing the second step could have caused the aforementioned observations. The second
199 hypothesis was supported at the knee joint first in terms of the knee flexor moment before toe-
200 off. The first step necessitated the participants to generate a greater knee flexor moment during
201 push-off phase. One plausible reason for this could be a difference in the end-points of the first
202 and second steps. Toe-off from the first step results in the limb being placed on the third stair of
203 the staircase but toe-off from the second step results in the limb placed on the platform of the top
204 of the stairs thus requiring lesser knee flexion. Probable differences in the muscle activation
205 patterns of the hamstrings (knee flexors) could also highlight a difference in the peak knee flexor
206 moments at both the steps. The second hypothesis was supported at the hip joint in terms of the
207 peak hip positive and negative powers. Greater peak hip positive power at foot-strike and lesser

208 peak hip negative power during toe-off on the second step compared to the first step could be
209 due to the difference in the end-points of the steps as discussed earlier.

210 Results procured in the present study matched those in the literature to a large extent
211 [8,11,18]. Irrespective of the condition or step, the joint moment profiles were similar to the ones
212 reported in other studies. However, some of the values in the present study fell beyond the range
213 reported in the literature. One reason we speculate for some out-of-range values is the slight
214 difference in methodology for stair ascent [8,11]. While the data analysis in the current study
215 examined at the first ipsilateral step from the first to the third step of the staircase, other studies
216 analyzed the data for the first ipsilateral step from the second to the fourth step of the staircase.

217 Investigating the benefit of ascending stairs with some gait speed assumes clinical
218 importance for aging and other pathological populations. The peak ankle positive power
219 generated before toe-off has been shown to be reduced for older adults [19]. Researchers also
220 reported that older adults produce peak knee extensor moment during stair ascent that is closer to
221 the maximum producing capacity of the knee extension moment [20]. Results from current study
222 suggest the need for a greater peak knee and hip extensor moment while ascending the first step
223 with gait speed. The amount of reduction in the required positive ankle power was less than the
224 amount of increase in the required knee and hip extensor moments when stair ascent is
225 performed with gait speed. These concentric knee and extensor moments play a crucial role for
226 weight-acceptance as well as lifting the body upward and forward [8]. Hence, results in the
227 current study could suggest that older adults and other populations with knee and hip problems
228 like osteoarthritis might find it particularly difficult to negotiate stairs with gait speed. However
229 another important factor to consider would be the effect of different walking speeds. Aging and
230 other pathological populations might approach the stairs more slowly. This could in turn cause

231 the peak values of joint moments and powers to fall within the range of those obtained during the
232 two conditions used in the current study. However, further research is needed to ascertain the
233 effect of aging and other neuromuscular disorders on stair ascent with different gait speeds.

234 **Conclusion**

235 While ascending the stairs starting from farther away, participants produced greater peak
236 knee and hip extensor moments and lesser ankle positive power at the first step. Participants also
237 produced greater peak plantiflexor moment, peak ankle negative power, peak hip positive power
238 while ascending the second ipsilateral step. These results identify the importance of the starting
239 position in experiments dealing with biomechanics of stair negotiation. Further, these findings
240 have important implications for studying stair ascent characteristics of other populations such as
241 older adults.

242 *Conflict of interest*

243
244 None.

245 **References**

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