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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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Abstract

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

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

Introduction

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

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

Interestingly, in previous research ascent was initiated exclusively directly in front of the stairway [9,10,11,12,13]. However, initiating stair ascent farther away from the stairs could allow participants to achieve a more natural gait speed before the transition phase from level walking to stepping on the stairway. This is actually the case many times when we negotiate stairs (for example at home or in a mall). Initiating stair ascent in front of the stairway would probably require more energy generation than initiating from farther away. This might influence magnitudes of both joint moments and powers. However, this information is currently unknown. Therefore, the objective was to address this knowledge gap and determine how different are the joint moments and powers when one begins stair ascent after achieving a comfortable gait speed compared to beginning stair ascent from a static position directly in front of the stairs. We hypothesized that the joint moments and powers during stair negotiation will be different between the two conditions. Additionally, these differences will appear in consecutive ipsilateral footfalls on the stairs.

Methods

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

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

Participants wore a tight-fitting suit and retro-reflective markers were placed on their pelvis and lower limbs based on modified Helen Hayes marker set [16]. All the participants were allowed to practice before testing. Also, in order to reduce the risk of falling while ascending the stairs, they were instructed to use the handrails if needed. However there were no trials involving a loss of balance or grabbing the handrails.

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

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

A repeated 2x2 ANOVA was performed. The factors were a) two consecutive footfalls on the stairway with the right limb (Steps 1 and 2; Figure 1) and b) two initial speed conditions of stair ascent (starting farther away from the stairway and starting in front of the stairway). The statistical analysis was performed using the SPSS software (SPSS Inc., Chicago, IL). The α-value was set at 0.05.

Results

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

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

For the peak hip extensor moment, the ANOVA results revealed a significant initial speed main effect (*P*=0.005) with the participants producing a 10% greater moment while ascending the stairs starting farther away (Table 1; Figure 2). However no significant step main effect (*P*=0.568) or interaction (*P*=0.500) were noted. For the peak hip flexor moment, a significant initial speed main effect (*P*=0.016) was observed where the moment was 16.5% greater when the participants ascended the stairs starting farther away (Table 1; Figure 2). There was no significant step main effect (*P*=0.308). A significant interaction (*P*=0.029) showed that when the participants started from farther away, the peak hip flexor moment decreased minimally (by 5%) from the first step to the second step. However, when stair ascent was initiated from in front of the stairs, the peak hip flexor moment increased (by 19%) from the first step to the second step (Figure 4B).

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

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

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

Discussion

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

The first hypothesis was supported by the ankle joint results in terms of the peak positive power before toe-off. When the participants started from farther away, the peak positive ankle power before toe-off at the first step was lesser compared to starting from in front of the stairs. This could be due to the fact that the gait speed prior to stepping on stairs allows one to move forward with additional momentum relying less at the ankle positive power to ascend the stairs. Further, the effect of the gait speed seemed to diminish on the second step where the participants needed greater peak ankle positive power to ascend further up. These observations also echoed for the peak plantiflexor moment before toe-off though no significant results were noted. The curve profiles from Figure 2 suggest that on the first step, participants seemed to generate lesser peak plantiflexor moment before toe-off when starting farther away from the stairs. Differences between both the conditions could also be spotted in Figure 2, in terms of lesser peak plantar flexion after foot-strike and greater peak dorsiflexion for stair ascent starting from afar. Nonetheless, no such characteristic distinctions between the conditions could be seen for the second step. The first hypothesis was also supported for the knee joint in terms of the peak knee extensor moment and the peak knee positive power following foot-strike. Particularly, the peak knee extensor moment was greater on the first step while ascending stairs starting farther away. At foot-strike, stair ascent demands more knee flexion compared to level-walking. Perhaps the participants generated a greater knee extensor moment to compensate for the change from level-walking to stairs. However, they did not have to worry about this factor while ascending from the front of the stairs. Also, once stair ascent was initiated, the difference in the peak knee extensor moment generated in both the conditions minimized at the second step.

The peak knee positive power at foot-strike decreased from the first step to the second step when the participants started from the front of the stairs. However when the participants started from farther away, this peak knee positive power remained relatively constant between the two steps. Comparisons between the peak knee joint positive power during extension and peak knee joint extensor moment could highlight the differences in the action of the quadriceps. For the condition of starting farther away, the quadriceps had to produce greater peak knee joint moment but lesser peak knee positive power at the first step. This could be due to a greater knee angular velocity while approaching stair ascent with a gait speed. The first hypothesis for the hip joint was also supported in terms of the peak hip extensor and flexor moments and the peak hip positive power. The curve profiles in Figure 2 indicated greater peak hip extensor and flexor moments when the participants started farther away, probably indicating the overall effect of gait speed on hip joint dynamics. Also, greater peak hip extensor moment would have translated to greater peak hip positive power by the hip extensors at foot-strike when the participants initiated stair ascent from farther away. The peak hip flexor moment showed characteristics similar to the peak knee extensor moment discussed above. The hip flexors probably generated greater hip flexor moment during toe-off at the first step while starting from afar due to the stair gait speed. However, the differences between the conditions were minimized at the second step due to change in stair gait speed during toe-off at the second step. Combined, these observations revealed that when participants ascended the stairs from farther away, the hip and knee extensors generated greater peak extensor moments and positive powers following foot-strike.

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

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

Investigating the benefit of ascending stairs with some gait speed assumes clinical importance for aging and other pathological populations. The peak ankle positive power generated before toe-off has been shown to be reduced for older adults [19]. Researchers also reported that older adults produce peak knee extensor moment during stair ascent that is closer to the maximum producing capacity of the knee extension moment [20]. Results from current study suggest the need for a greater peak knee and hip extensor moment while ascending the first step with gait speed. The amount of reduction in the required positive ankle power was less than the amount of increase in the required knee and hip extensor moments when stair ascent is performed with gait speed. These concentric knee and extensor moments play a crucial role for weight-acceptance as well as lifting the body upward and forward [8]. Hence, results in the current study could suggest that older adults and other populations with knee and hip problems like osteoarthritis might find it particularly difficult to negotiate stairs with gait speed. However another important factor to consider would be the effect of different walking speeds. Aging and other pathological populations might approach the stairs more slowly. This could in turn cause the peak values of joint moments and powers to fall within the range of those obtained during the two conditions used in the current study. However, further research is needed to ascertain the effect of aging and other neuromuscular disorders on stair ascent with different gait speeds.

Conclusion

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

Conflict of interest

None.

References

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