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Frontal Joint Dynamics when Initiating Stair Ascent from a Walk versus a Stand

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Abstract

Ascending stairs is a challenging activity of daily living for many populations. Frontal plane joint dynamics are critical to understand the mechanisms involved in stair ascension as they contribute to both propulsion and medio-lateral stability. However, previous research is limited to understanding these dynamics while initiating stair ascent from a stand. We investigated if initiating stair ascent from a walk with a comfortable self-selected speed can affect the frontal plane lower-extremity joint moments and powers as compared to initiating stair ascent from a stand and if this difference would exist at consecutive ipsilateral steps on the stairs. Kinematics data using a 3-D motion capture system and kinetics data using two force platforms on the first and third stair treads were recorded simultaneously as ten healthy young adults ascended a custom-built staircase. Data were collected from two starting conditions of stair ascent, from a walk (speed: 1.42±0.21m/s) and from a stand. Results showed that subjects generated greater peak knee abductor moment and greater peak hip abductor moment when initiating stair ascent from a walk. Greater peak joint moments and powers at all joints were also seen while ascending the second ipsilateral step. Particularly, greater hip abductor moment was needed to avoid contact of the contralateral limb with the intermediate step by counteracting the pelvic drop on the contralateral side. This could be important for therapists using stair climbing as a testing/training tool to evaluate hip strength in individuals with documented frontal plane abnormalities (i.e. knee and hip osteoarthritis, ACL injury).

Keywords: Stair climbing; Joint moments; Joint powers; Walking; Stair ambulation; Abductor Muscles; Adductor Muscles

1. Introduction

Older adults frequently experience falls while negotiating stairs (Rubenstein 2006; Hemenway et al., 1994). Hence, understanding fall-related mechanisms via examining the joint dynamics (moments and powers) has been a research area of great interest (McFadyen and Winter, 1988; Startzell et al., 2000; Reeves et al., 2008). Particularly, the frontal plane dynamics contribute to both propulsion and medio-lateral stability (Nadeau et al., 2003; Novak and Brouwer, 2011) and are critical at the knee and hip joints (Andriacchi et al., 1980; Kowalk et al., 1996; Costigan et al., 2002). These two joints experience external adductor moments (Kowalk et al., 1996) and compared to level-walking, these moments are lesser at the hip and greater at the knee (Costigan et al., 2002; Nadeau et al., 2003). These moments have also been shown to be similar for two consecutive steps (Kowalk et al., 1996). Examining the frontal plane dynamics during stair negotiation could play a pivotal role in rehabilitation of people with weak hip abductors and with knee problems (Nadeau et al., 2003).

Importantly, the currently available literature only includes studies where stair ascent was initiated from a stand. However, initiating stair ascent from a walk is much more common at private and public locations. Thus to increase external validity in the stair negotiation research, it is important to consider such a condition. Such an approach immediately generates several crucial questions: Does ascending stairs from a walk require greater moments and more power to maintain frontal plane stability as compared to initiating stair ascent directly from a stand? And if such differences exist, are they present only at the first step of the staircase or also at the next ipsilateral step? Previous work has shown that ascending stairs starting from a walk caused higher peak knee and hip extensor moments in the sagittal plane as compared to starting stair ascent from a stand and altered lower-extremity joint moments and powers between two consecutive ipsilateral steps (Vallabhajosula et al., in press). Such differences could also result in different joint moments and powers to maintain medio-lateral stability during stair ascent after starting from a walk or a stand. Therefore, the objective of the present study was to determine frontal plane joint dynamics when one ascends stairs from a walk compared to ascending stairs from a stand. Due to enhanced momentum when initiating stair ascent from a walk (increased velocity) compared to initiating stair ascent from a stand, we hypothesized that the frontal plane joint moments and powers will be greater when 1) ascending stairs from a walk and 2) at the next ipsilateral step.

2. Methods

Ten healthy subjects (three females; 26.4±3.7years; 76.2±13.6kg; 1.78±0.08m) signed an informed consent approved by the local institutional review board. Inclusion criteria were: age between 19-35 years and free of any injury that could alter gait. Exclusion criteria were: presence of any known disorder(s) that may affect gait or the inability to negotiate a stairway.

Kinematic (Motion Analysis Corp., Santa Rosa, CA; 60 Hz) and kinetic data using two force platforms embedded in the first and the third stair treads of an instrumented stairway (Advanced Mechanical Technology Inc., Watertown, MA; 600 Hz) were collected (Figure 1). The force platforms were isolated from the rest of the structure to avoid vibration artifacts (similar to Holsgaard-Larsen et al., 2011).

Retro-reflective markers were placed on subjects' pelvis and lower limbs based on modified Helen Hayes marker set (Houck et al., 2005). Before testing, all the subjects were allowed to practice stair ascension without using handrails. During testing, none of the subjects used the handrails. Subjects wore comfortable sport shoes and walked towards the stairs at their self-selected comfortable speed from a distance of 5m. Their speed was calculated based on the time recordings of two photocells positioned 2m apart in front of the stairway (Figures 2A,2B). An average walking speed (1.42±0.21m/s) from 16 such trials was used as the self-selected comfortable speed for each subject. Next, the subjects ascended stairs five times in two conditions, starting with the right limb for each condition: 1) initiating stair ascent from a walk (condition 1; Figures 2A,2B), and 2) initiating stair ascent from a stand (condition 2; Figures 2C,2D). An acceptable trial for condition 1 required the subject to ascend the stairway within ±10% of the self-selected comfortable speed. Data were collected until five acceptable trials were procured. The order of the conditions was randomized.

Peak internal abductor and adductor moments, and peak power generated and absorbed at ankle, knee, and hip joints were used as the dependent variables (Costigan et al., 2002; Nadeau et al., 2003). They were calculated for two consecutive ipsilateral steps on the staircase during both conditions using a custom-written Matlab (MathWorks Inc., Natick, MA, USA) program. For each subject, and for each condition, the maximum and minimum joint moments and powers from the five trials were averaged to calculate the mean values. Group means and standard deviations were then obtained by averaging these mean peak values. A fully repeated two-way ANOVA (condition X step) was performed using SPSS (International Business Machines, Armonk, NY) with α-value set at 0.05.

3. Results

Subjects produced significantly greater peak abductor moments at the knee (3%; P=0.014) and hip (7%; P=0.006) when initiating stair ascent from a walk (Figure 3A). Subjects produced significantly greater peak ankle (20%; P=0.007), knee (20%; P<0.001) and hip abductor moments (20%; P<0.001) at the second ipsilateral step (Figure 3B). There were no significant interactions.

Subjects generated significantly greater peak power at the ankle (48%; P=0.023), knee (43%; P=0.002) and hip (42%; P=0.003) at the second ipsilateral step (Figure 3C). Subjects also absorbed significantly greater peak power at the ankle (44%; P=0.001), knee (50%; P=0.003) and hip (64%; P=0.014) at the second ipsilateral step (Figure 3D). There was no significant main effect for starting positions or significant interaction.

4. Discussion

Due to enhanced momentum when initiating stair ascent from a walk (increased velocity) compared to initiating stair ascent from a stand, we hypothesized that the frontal plane joint dynamics would be greater as one ascends stairs from a walk and such differences would be augmented in the next ipsilateral step. Collectively, our results supported both hypotheses. The greater peak knee abductor moment when initiating stair ascent from a walk demonstrates that the lateral portions of the knee experience higher levels of stress. Greater peak hip abductor moment when initiating stair ascent from a walk (Figure 3A) indicates an increased activity of the ipsilateral hip abductors. This increased activity could assist the contralateral limb to avoid contact with the intermediate step by counteracting the pelvic drop on the contralateral side (Kirkwood et al., 1999; Nadeau et al., 2003). Also, initiating stair ascent from a walk could have resulted in greater velocity and hence greater peak joint moments at knee and hip joints. Based on previous literature, a 3% difference between the peak knee abductor moments during both the conditions might only be statistical (Costigan et al., 2002). However, the 7% difference between the peak hip abductor moments suggests that ascending stairs from a walk could be more challenging compared to ascending stairs from a stand (Nadeau et al., 2003). This could be an important finding in the literature concerning people with weaker hip abductors, e.g. hip arthroplasty and osteoarthritis. Such individuals may not be able to generate sufficient moments to counteract the pelvic drop on the contralateral side, possibly resulting in a mechanically inefficient stair ascent. Similar joint powers in both conditions could indicate greater angular velocity at the knee and hip joints during the second condition. Also, similar peak ankle joint moments and powers between the two conditions could be due to the relatively small contribution of the ankle joint to frontal plane stability while ascending stairs (Nadeau et al., 2003).

Greater peak moments and powers while ascending the second ipsilateral step (Figures 3B-D) highlight the greater effort needed to maintain stability in the frontal plane or to help the contralateral leg move to clear the intermediate step as one ascends. Electromyography data in future studies could highlight how different muscle loadings contribute to this greater effort. The joint moment profiles and values in the current study were similar to the ones reported in the literature (Kirkwood et al., 1999; Nadeau et al., 2003; Novak and Brouwer, 2011; Table 1). The three lower-extremity joints largely experienced abductor moments throughout the stance phase (Figure 4). One plausible reason is the passage of the ground reaction force vector medially with respect to the joint centers (Kirkwood et al., 1999).

5. Conclusion

Results from the present study demonstrated that the knee and hip joints experience greater peak abductor moments when initiating stair ascent from a walk and at the next ipsilateral step. These findings could provide therapists a comprehensive understanding of the mechanisms involved during stair climbing when used as a training/testing module for evaluating hip strength. In addition, results have methodological implications for the stair negotiation biomechanical research, especially in individuals with documented frontal plane abnormalities (i.e. knee and hip osteoarthritis, ACL injury).

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