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Anticipatory kinematics and muscle activity preceding transitions from level-ground walking to stair ascent and descent

Joshua Peng [a,b,1], Nicholas P. Fey [a,c,*,1], Todd A. Kuiken [a,b,c], Levi J. Hargrove [a,c]

[a] Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, IL 60611, USA
[b] Department of Biomedical Engineering, Northwestern University, Chicago, IL 60611, USA
[c] Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, IL 60611, USA

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ABSTRACT

The majority of fall-related accidents are during stair ambulation—occurring commonly at the top and bottom stairs of each flight, locations in which individuals are transitioning to stairs. Little is known about how individuals adjust their biomechanics in anticipation of walking-stair transitions.

We identified the anticipatory stride mechanics of nine able-bodied individuals as they approached transitions from level ground walking to stair ascent and descent. Unlike prior investigations of stair ambulation, we analyzed two consecutive "anticipation" strides preceding the transitions strides to stairs, and tested a comprehensive set of kinematic and electromyographic (EMG) data from *both* the leading and trailing legs. Subjects completed ten trials of baseline overground walking and ten trials of walking to stair ascent and descent. Deviations relative to baseline were assessed.

Significant changes in mechanics and EMG occurred in the earliest anticipation strides analyzed for both ascent and descent transitions. For stair *descent*, these changes were consistent with observed reductions in walking speed, which occurred in all anticipation strides tested. For stair *ascent*, subjects maintained their speed until the swing phase of the latest anticipation stride, and changes were found that would normally be observed for decreasing speed.

Given the timing and nature of the observed changes, this study has implications for enhancing intent recognition systems and evaluating fall-prone or disabled individuals, by testing their abilities to sense upcoming transitions and decelerate during locomotion.

1. Introduction

In urban environments, 40% of a person's daily walking tasks are non-steady, short-duration bouts of fewer than 12 steps (Orendurff et al., 2008). Understanding how people transition between these bouts is important—especially transitions that involve changing to a different mode of ambulation with altered mechanical demands—as such transitions may increase the risk of falling and sustaining fall-related injuries.

The majority of fall-related accidents occur during stair ambulation (CDC, 2010). Moreover, the three stairs at the bottom and top of staircases, where individuals transition onto and from the stairs, respectively, are the most common locations for missteps and falls (Sheldon, 1960; Wild et al., 1981; Templer, 1992). Transitions from level ground to stairs are among the most challenging and hazardous tasks performed during community living. This is especially true for individuals with physical limitations, including older adults (Lee and Chou, 2007), stroke survivors (Laufer et al., 2000), and lower-limb amputees (Bae et al., 2009). Developing device or rehabilitative interventions to improve outcomes for such individuals requires a comprehensive understanding of how able-bodied individuals transition from level-ground walking to stairs.

To our knowledge, no study has investigated the anticipatory mechanics of able-bodied individuals during the strides preceding transitions from level-ground walking to stairs. Although, studies have examined the individual transition strides between walking and stairs. Yet, these studies were not focused on comprehensively comparing mechanics and muscle activity (i.e., electromyography) (e.g., McFadyen and Carnahan, 1997; Lee and Chou, 2006) or mechanics of the hip and knee in conjunction with the ankle (e.g., Gates, 2004). More commonly, the strides on the stairs following

* Correspondence to: Rehabilitation Institute of Chicago, 345 East, Superior Street, Suite 1309, Chicago, IL 60611, USA. Tel.: +1 312 238 1566; fax: +1 312 238 2081.
E-mail address: nfey@ricres.org (N.P. Fey).
[1] Co-first authors (equal contributions).

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the transition strides (i.e., the stair strides) have been analyzed. Other investigations have shown that step length parameters two strides preceding the transition to curbs (Crosbie, 1996) are modified in anticipation of the new surface. Given an assumed higher demand associated with stairs, we expect similar and more substantial gait modifications may be identified prior to stair transitions. Identifying these modifications would fill a knowledge gap and could allow for improved design of rehabilitation protocols and assistive devices for individuals with disabilities.

The purpose of this study was to identify the anticipatory stride mechanics of able-bodied individuals as they approach transitions from level ground walking to stair ascent and descent. We compared bilateral kinematics of the hip, knee and ankle, center-of-mass kinematics, spatiotemporal stride characteristics as well as electromyography (EMG) of muscles spanning the lower-limb. We hypothesized that significant changes in these characteristics would be found in two anticipation strides of the leading and trailing limbs preceding transitions to *both* stair ascent and descent. To transition to stair ascent and continue ambulating up stairs, a person must increase their net mechanical energy (i.e., sum of kinetic and potential energies). This change could occur during anticipation on level ground, when net changes in potential energy are zero. Thus, we further hypothesized that the transitions to stair ascent would result in anticipatory mechanics and EMG that were consistent with increasing the overall energetics of the body (i.e., increasing walking speed), while transitioning to stair descent would result in anticipatory mechanics and EMG that were consistent with decreasing the overall energetics of the body (i.e., decreasing walking speed).

2. Methods

2.1. Protocol

Nine adults (4 males, 5 females) consented to the IRB approved protocol. All subjects reported no known pathologies, and were capable of ascending and descending a staircase without external assistance. Subjects completed 10 trials of steady-state level walking, level walking to stair ascent and level walking to stair descent (Fig. 1). They were instructed to walk at their self-selected speed in all trials and conditions. Level walking occurred across a 10-m walkway. In the stair conditions, a custom built 4-step staircase was used, containing 7.5 in. risers and 12 in. treads (Fig. 1). Elevated platforms were placed adjacent to the stair case. In the stair conditions, subjects were asked to lead with a foot of their preference, and to maintain this convention across trials and conditions. The walkway preceding the staircase was 6.2 m and 5.2 m in length for ascent and descent conditions, respectively. These dimensions were constrained by the size of the gait lab.

2.2. Kinematics and electromyography

An 8-camera motion capture system (Motion Lab Systems, Inc.) was used to measure kinematics of the legs, pelvis and trunk (120 Hz). Forty reflective markers were placed bilaterally on the trunk, pelvis and lower-limbs (Fig. 1). In addition, markers were placed at the first, second, and fifth metatarsal heads on the outside of their shoes (Fig. 1). Joint and center-of-mass kinematics were calculated in Visual3D (C-Motion, Inc.).

Surface EMG were recorded at 1200 Hz (Delsys, Inc.), using a 500 Hz anti-aliasing low-pass hardware filter. Electrodes were placed bilaterally over 12 muscles including the gluteus maximus, gluteus medius, adductor magnus, semitendinosus, biceps femoris, rectus femoris, vastus lateralis, vastus medialis, tibialis anterior, gastrocnemius lateralis, gastrocnemius medialis, and soleus. EMG were band-pass filtered (40–450 Hz), and envelopes were created by applying a full wave rectification and a low-pass 5 Hz filter. For each muscle, smoothed EMG magnitudes were normalized to the maximum EMG value of the baseline walking condition.

2.3. Analyses

Data from baseline level-ground walking and two consecutive anticipation strides (Fig. 2) for both the leading and trailing legs, preceding the stair transition strides, were extracted. Mean values of each metric were computed over the stance and swing phase were as well as over 200 ms time windows preceding toe-off (terminal stance phase) and heel-strike (terminal swing). Paired *t*-tests were used to compare these metrics of each anticipation stride to the corresponding values from the same leg obtained during baseline level-ground walking trials. A Bonferroni correction was used to adjust the standard significance level to $\alpha/n=(0.05/3)=0.0167$, since baseline level-ground walking and two anticipation strides were compared for each leg. Spatiotemporal stride parameters were also compared in this manner.

3. Results

3.1. Center-of-mass kinematics

In anticipation strides preceding stair ascent, we observed no changes in the mean anterior translation or velocity of the center-of-mass in stance (Fig. 3). We found a decreased center-of-mass velocity in the second anticipation stride of the trailing leg in terminal swing and throughout swing (i.e., the latest portion of the latest anticipation stride).

Changes in center-of-mass kinematics occurred earlier regarding stair descent. We observed a slower velocity in terminal stance, throughout stance and throughout swing of the first anticipation stride of the leading leg (i.e., the entirety of the earliest anticipation stride) (Fig. 3). Corresponding reductions in center-of-mass translation were observed in the first anticipation stride of the leading leg. We also

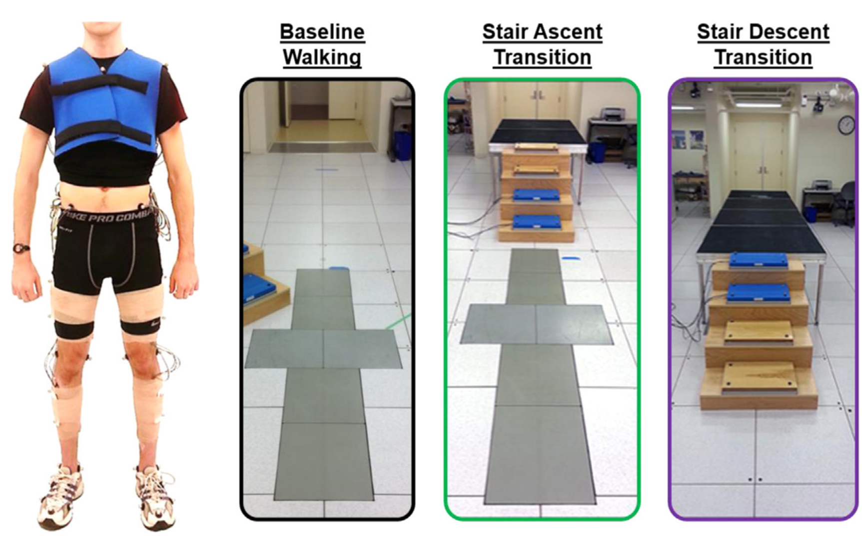

Fig. 1. Representative instrumented subject (left) and diagram of the lab setup during baseline walking, stair ascent and stair descent conditions (right).