Journal of Biomechanics 48 (2015) 921–929

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Biomechanical analyses of stair-climbing while dual-tasking

Srikant Vallabhajosula [a,*], Chi Wei Tan [b], Mukul Mukherjee [b], Austin J. Davidson [b], Nicholas Stergiou [b,c]

[a] Department of Physical Therapy Education, School of Health Sciences, Elon University, Elon, NC, United States
[b] Biomechanics Research Building, School of Health, Physical Education and Recreation, College of Education, University of Nebraska at Omaha, Omaha, NE, United States
[c] College of Public Health, University of Nebraska Medical Center, Omaha, NE, United States

ARTICLE INFO

Article history:
Accepted 15 February 2015

Keywords:
Working memory
Counting backwards
Stair negotiation
Stair ascension
Multi-tasking
Stepping

ABSTRACT

Stair-climbing while doing a concurrent task like talking or holding an object is a common activity of daily living which poses high risk for falls. While biomechanical analyses of overground walking during dual-tasking have been studied extensively, little is known on the biomechanics of stair-climbing while dual-tasking. We sought to determine the impact of performing a concurrent cognitive or motor task during stair-climbing. We hypothesized that a concurrent cognitive task will have a greater impact on stair climbing performance compared to a concurrent motor task and that this impact will be greater on a higher-level step. Ten healthy young adults performed 10 trials of stair-climbing each under four conditions: stair ascending only, stair ascending and performing subtraction of serial sevens from a three-digit number, stair ascending and carrying an empty opaque box and stair ascending, performing subtraction of serial sevens from a random three-digit number and carrying an empty opaque box. Kinematics (lower extremity joint angles and minimum toe clearance) and kinetics (ground reaction forces and joint moments and powers) data were collected. We found that a concurrent cognitive task impacted kinetics but not kinematics of stair-climbing. The effect of dual-tasking during stair ascent also seemed to vary based on the different phases of stair ascent stance and seem to have greater impact as one climbs higher. Overall, the results of the current study suggest that the association between the executive functioning and motor task (like gait) becomes stronger as the level of complexity of the motor task increases.

1. Introduction

Stair ascent is a common functional and challenging task for several populations. For instance, older adults are at a greater risk for a stairs-related fall due to biomechanical, perception-action or environmental constraints (Startzell et al., 2000) and exhibit altered stair-gait characteristics (Novak and Brouwer, 2011; Reeves et al., 2009; Lee and Chou, 2007; Stacoff et al., 2005; Larsen et al., 2009). Previous researchers have also documented stairs-related difficulties for patients with stroke (Novak and Brouwer, 2012), total hip arthoplasty (Lamontagne et al., 2011), and knee osteoarthritis (Asay et al., 2009). The risk of falls during stair-climbing further increases while performing concurrent tasks like talking and/or carrying an object (Startzell et al., 2000; Ojha et al., 2009; Muhaidat et al., 2011).

There is significant work examining the gait during overground walking using dual-tasking paradigms (Abernethy, 1988; Ebersbach et al., 1995; Sparrow et al., 2002; Beauchet et al., 2005a, b; Siu et al., 2008). During overground walking, an additional cognitive task caused reduction in speed, cadence, and stride length while stride and double support time increased (Al-Yahya et al., 2011; Nadkarni et al., 2010). Cognitive tasks interfering internally (such as counting backwards) have a greater impact on changes in gait than those interfering externally such as reaction time tasks (Al-Yahya et al., 2011). This might be because internal interfering tasks require the use of working memory, which places an additional load on an individual while walking. 'Working memory' denotes a system used for storing and manipulating information related to complex cognitive tasks on a temporary basis (Baddeley, 1992). Researchers have also implicated that supraspinal control of gait is associated with decline in working memory in persons with balance impairments (Siu et al., 2008), mild cognitive impairment (Montero-Odasso et al., 2009), multiple sclerosis (Hamilton et al., 2009), in community-dwelling older females (Priest et al., 2008). A majority of these experimental paradigms had participants performing level walking or obstacle clearance but

* Correspondence to: Department of Physical Therapy Education, Elon University, CB 2085, 762 East Haggard Ave., Elon, NC 27244, United States.
Tel.: +1 336 278 6402; fax: +1 336 278 4914.
E-mail address: svallabhajosula@elon.edu (S. Vallabhajosula).

http://dx.doi.org/10.1016/j.jbiomech.2015.02.024
0021-9290/

stair-climbing has received scant attention. This is surprising given that stair-climbing is a common activity of daily living.

Biomechanics of stair-climbing (under single-task condition) is quite pervasively studied in healthy young adults. Commonly used parameters include lower-extremity joint angles (McFadyen and Winter, 1988; Protopapadaki et al., 2007), moments and powers (McFadyen and Winter, 1988; Costigan et al., 2002; Spanjaard et al., 2008; Vallabhajosula et al., 2012a, b), ground reaction forces (Stacoff et al., 2005), and foot clearance (Hamel et al., 2005). During the stance phase of stair ascent, the hip and the knee joints undergo extension while the ankle joint undergoes plantar flexion (McFadyen and Winter, 1988). Also, the vertical ground reaction force profile is characterized by two peaks with the second peak greater than the first (McFadyen and Winter, 1988). Joint moments and powers differ between lower-level and higher-level steps in both sagittal and frontal planes (Vallabhajosula et al., 2012a, b). Also, Ojha et al. (2009) highlighted that older adults required more attentional resources compared to younger adults during stair-climbing while dual-tasking. However, there is lack of research on thorough biomechanical analyses of stair-climbing among healthy young adults under dual-tasking conditions and is warranted given how frequently one climbs stairs performing a concurrent task. Such information has ecological validity as it allows us to understand the factors that could increase the risk of falls during stair-climbing while performing concurrent tasks.

It is speculated that gait is primarily regulated using the cortical inputs to the brain-stem, spinal and cerebellar regions. An additional cognitive task that involves working memory used by prefrontal cortex regions might have different implications than adding an additional motor task that might involve the motor cortex regions. Furthermore, both the concurrent cognitive and motor tasks present different environmental challenges to the person as the secondary motor task like carrying an object might involve reduced/altered visual input and increased use of peripheral resources. Paul et al. (2009) showed that persons with diabetes mellitus walked with a smaller step length and greater double-support time while performing a concurrent motor task compared to performing a concurrent cognitive task, and there was no effect on walking speed, cadence or step time. Using different tasks, O'Shea et al. (2002) showed that there was no difference between the effects of secondary cognitive or motor tasks during gait among persons with Parkinson's disease. While this is useful, stair-climbing is considered a more strenuous motor task compared to gait and the effects of concurrent cognitive and motor tasks during stair-climbing has the potential to highlight the role of supraspinal control of locomotion.

The purpose of the current study was to determine the impact of performing a concurrent cognitive or motor task while stair-climbing. We hypothesized that a concurrent cognitive task will have a greater impact on stair-climbing performance compared to a concurrent motor task. We also hypothesized that this impact will be greater at the higher-level step compared to the lower-level step.

2. Methods

Ten participants (four females, age: 23.9 ± 2.8 years, height: 1.76 ± 0.06 m, mass: 71.3 ± 8.61 kg), signed an informed consent form approved by the local institutional review board. Inclusion criteria: age between 19 and 35 years, and no history of injuries that could impair gait. Exclusion criteria: presence of any known disorders that may affect gait pattern or ability to ambulate stairs without using handrails.

Kinematic data were collected at 60 Hz using eight cameras (Motion Analysis System, Santa Rosa, CA). Kinetic data were collected at 600 Hz using two force platforms (AMTI, Watertown, MA) embedded in the lower-level and the higher-level steps, of a four-step instrumented staircase (Fig. 1; see Vallabhajosula et al., 2012a, b for dimensions).

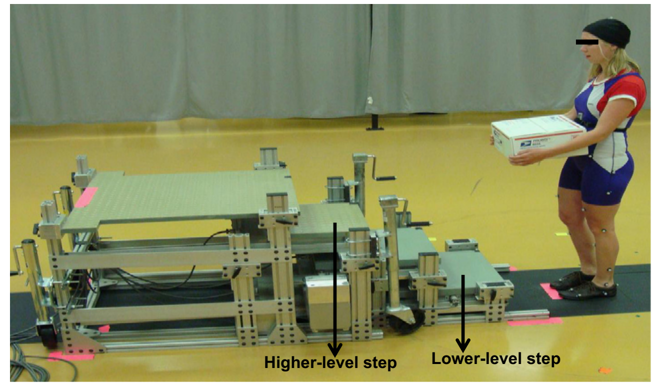

Fig. 1. Picture of experimental set-up. Participants started each trial in all the four experimental conditions: ascending the stairs without counting and carrying a box (C1), ascending the stairs while counting backwards and not carrying a box (C2), ascending the stairs while carrying a box and not counting (C3), ascending the stairs while counting backwards and carrying a box (C4); the participants always started from a standing position in front of the staircase; participants took first step with their dominant leg; dependent variables were collected for both the lower-level and higher-level steps.

Retro-reflective markers based on the modified Helen Hayes marker set (Davis et al., 1991) were placed on participants wearing tight-fitting suits. Additionally, one marker was placed on the edge of each step. Ten trials were collected in each of the four conditions: (C1) stair ascending only – control, (C2) stair ascending and performing subtraction of serial sevens from a three-digit number – cognitive, (C3) stair ascending and carrying an empty opaque box (12.25″ × 12.25″ × 6″; 0.28 kg) – motor and (C4) stair ascending, performing subtraction of serial sevens from a random three-digit number and carrying an empty opaque box (12.25″ × 12.25″ × 6″; 0.28 kg) – combined. Counting backwards by sevens is a commonly used working memory task of sufficient difficulty. The order of the conditions was randomized.

Before data collection began, all participants were tested to be right leg dominant. Dominance was determined by noting which leg the participant preferred to kick a soccer ball. During all the conditions, participants stood with their toes aligned 15 cm in front of the lower-level step and looking straight ahead. Upon receiving a visual cue from the experimenter, participants began stair ascent starting with their right leg (onto the lower-level step). For C2 and C4, participants began counting prior to receiving the visual cue. For C3 and C4, participants held the box to their chest. No further instructions were provided. The participants ascended the stairs in a step-over-step manner. They stopped walking and counting once they reached the end of the stairs. The participants practiced till they were confident of performing the task under each condition.

Using a custom-made Matlab (Mathworks Inc., Natick, MA) script, the following dependent variables were calculated for the stance phase of the lower-level and higher-level steps (two consecutive ipsilateral steps; Fig. 1): average speed, two peak vertical forces, loading rate (of the first peak vertical force), minimum force during mid-stance, peak braking and propulsion forces, peak joint angles, range of motion, peak joint moments and powers. The stance phase was defined as the time period between right foot heel-strike to right foot toe-off. Further, minimum toe clearance (MTC) in the anterior and vertical directions was calculated for right foot at both the steps. MTC was defined as the shortest distance between the toe and the edge of the step before the toe crossed the vertical plane of the step. For each condition, an average of 10 trials was used for data analysis.

A 2 (Steps) × 4 (Conditions) repeated measures ANOVA was performed for all the variables using the SPSS software (IBM, Armonk, NY). When significant main effects were found, Bonferroni pairwise comparisons were used to determine the significant differences among the conditions. An α-value of 0.05 was used.

3. Results

Joint angles and ground reaction forces based dependent measures are presented in Table 1. Joint moments, powers, MTC and speed based dependent measures are presented in Table 2. Variables that showed significant step main effects are presented in Table 3. Variables that showed significant condition main effects are presented in Fig. 2. Variables that showed significant interaction are presented in Fig. 3. Outcome measures were normalized by subjects' mass. Figs. 4–7 show the profiles of the joint angles, ground reaction forces, joint moments and joint powers respectively across all conditions and steps.