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Journal of Biomechanics 40 (2007) 3641–3649

JOURNAL OF BIOMECHANICS

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Balance control in stepping down expected and unexpected level changes

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Accepted 12 June 2007

Abstract

Stepping down an elevation in ongoing gait is a common task that can cause falls when the level change is unexpected. The aim of this study was to compare expected and unexpected stepping down. We hypothesized that unexpected stepping would lead to loss of control over the movement and potentially falls due to buckling of the leading leg at landing. Ten male subjects repeatedly walked over a platform on which they stepped down an expected 10-cm height difference. In 5 out of 50 trials, the height difference was encountered unexpectedly early. Kinematics and ground reaction forces under both feet were measured during the stride in which the height difference was negotiated. Stepping down involved a substantial increase in forward horizontal and angular momenta (approximately 40 N s and 20 N m s). In expected stepping down, step length was significantly increased (17%), which allowed control of these forward horizontal and angular momenta immediately following landing. In unexpected stepping down, the time between expected ground contact and actual ground contact (110 ms) appeared too short to substantially adjust leg movement and increase step length. Although buckling of the leg did not occur, presumably due to its more vertical orientation at landing, momentum could not be sufficiently attenuated at landing, but a fall was prevented by a rapid step of the trailing limb. The lack of control of momentum might cause a fall, when the capacity to make such a rapid step falls short, as in the elderly, or when the height difference is larger.
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Keywords: Gait; Balance; Falls

1. Introduction

Fall-related morbidity and mortality are high in the industrialized world. In the USA, for example, falls are the second largest source of unintentional fatal injuries (Fingerhut et al., 1998) and the leading cause of nonfatal injuries (Warner et al., 2000). Especially individuals above 65 years of age are at risk for falls (for overview, see Tideiksaar, 1997; Lord et al., 2001).

Age-related changes in neuromotor capacity, such as muscle weakness and increased response times, have been associated with fall risk in observational studies (e.g. Lord et al., 2001; Stel et al., 2003). Mechanical analyses of balance perturbations and recovery reactions can complement such data from observational studies with more detailed insight into factors determining fall risk (Dieën et al., 2005). Since most falls occur during gait (Berg et al., 1997), gait and perturbations of gait have received much attention in studies aimed at the prevention of falls. However, while gait on even surfaces has been extensively studied, negotiation of uneven surfaces is comparatively uncharted. Stepping down an elevation in ongoing gait is a common task and frequently causes falls when the level change is unexpected. In a 1-year prospective study of falls among adults over 60 years old, misplaced steps such as stepping into a hole formed the third cause of falls after tripping and slipping and accounted for 12% of all cases (Berg et al., 1997).

When stepping down an elevation, potential energy is lost and kinetic energy gained, resulting in increased linear and/or angular momentum. To our knowledge, no data

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0021-9290/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2007.06.009

have been reported on how these momenta are controlled in stepping down in ongoing gait. In stair descent, negative power at the knee and ankle of the landing leg reduces the kinetic energy (McFadyen and Winter, 1988; Riener et al., 2002). To this end, leg extensor muscles are activated prior to touch down on the lower level and subsequently, the extensor muscle–tendon complexes are stretched absorbing energy (Spanjaard et al., 2007). Leg alignment and muscle activation determine leg stiffness at landing (Hortobagyi and DeVita, 1999, 2000) and hence the ability to absorb kinetic energy without undue joint rotations. Since the preparatory actions to attain proper leg alignment and muscle activation at landing are likely to be absent or inadequate in unexpected stepping down, we hypothesized that leg stiffness would be insufficient in unexpected stepping down, leading to buckling of the landing leg, as observed in landing after experimentally induced trips (Pavol et al., 2001). Furthermore, leg placement relative to the body center of mass is crucial for control of momentum (Grabiner et al., 1993; Pavol et al., 2001). Therefore, we hypothesized that linear and angular momenta would be less adequately controlled in unexpected than in expected stepping down.

2. Methods

Ten healthy young male subjects (age: 23.1 years (22–24 years), height: 1.85 m (1.75–1.99 m) and body mass: 76.8 kg (68–90 kg)) participated in the study. The experimental protocol had been approved by the local ethics committee and all subjects signed informed consent.

Subjects walked over a 10-m platform at 5 km/h (Fig. 1), wearing comfortable shoes. Walking speed was imposed by instructing subjects to walk alongside a series of flags on a cable that ran over two pulleys, driven by an electromotor. Just after crossing half of the length of the platform, they stepped down a 10-cm height difference. Subjects first performed 10 practice trials. Subsequently, they were informed that they could experience an unexpected step down, but not on how and when this would occur. Unexpected steps down were caused in 5 randomly selected trials out of a total of 50 trials, by taking away a 130-cm-long part of the platform (Fig. 1). The step down thus appeared earlier than expected. Glasses, blinding the lower half of the visual field, ensured that subjects were not aware of this. Between trials, they wore a headphone playing loud music to ensure that manipulations with the platform remained unnoticed. A full-body safety harness, attached to a ceiling-mounted rail, prevented subjects from falling (Pijnappels et al., 2004). Ten control trials were performed for expected stepping down in the same place as in the preceding unexpected trials. Note that, due to the glasses, the level change was never visible to the subject. In the expected condition, however, an orange flag at eye level and thus visible to the subject marked its location. Stepping down can be done using a toe or heel landing (Freedman and Kent, 1987). First, five trials were recorded in which the subject used his self-selected strategy (heel landing in nine subjects). The next five trials were performed with the other strategy. Since all unexpected trials involved a heel landing, only the heel landing trials were used for comparison of expected and unexpected stepping down.

Prior to the experiment, infrared light emitting markers were placed bilaterally on anatomical landmarks: on the shoe over the fifth metatarso-phalangeal joint, lateral malleolus, lateral femur epicondyle, major trochanter and acromial process. A 3×3 camera system (Optotrak® Northern Digital Inc., Waterloo, Ont.) was used to record positions of these markers at 100 samples/s. Ground reaction forces were recorded at 1000 samples/s using two custom-made 1.0×1.0 m force plates. Optotrak and force plate data were filtered (bidirectional second order low-pass Butterworth, cut-off frequency of 20 Hz). A 2D inverse dynamics model was used to calculate internal joint moments and joint powers. The coordinates of the anatomical landmarks defined seven segments: two feet, two lower legs, two upper legs and a head–arms–trunk (HAT) segment. Segment inertial parameters, center of mass (COM) positions and moments of inertia were estimated for each subject according to Plagenhoef et al. (1983).

The analysis focused on the last stance phase at the higher level (trailing leg) and the first stance phase at the lower level (leading leg). Changes in linear and angular momentum during these phases were calculated from the areas under the curves of the ground reaction forces and their resulting external moments about the body COM. The averaged position of the hip markers was used as an approximation of COM, because these markers were visible longer than the full set of markers needed to estimate COM.

To test the hypothesis that buckling of the leading leg occurs after unexpected stepping down, peak flexion angles of the leading leg in the first 200 ms after landing were compared between expected and unexpected stepping down. Furthermore, peak joint moments and peak

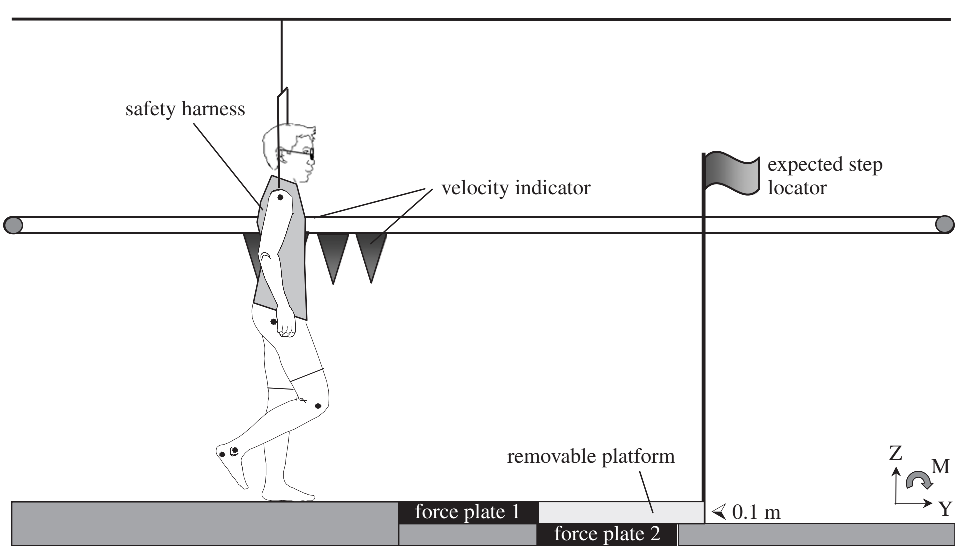

Fig. 1. Experimental setup: subjects wore glasses and a safety harness. The flag indicates the expected height difference; light grey part on the second force plate is a removable platform.

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