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Beam walking can detect differences in walking balance proficiency across a range of sensorimotor abilities

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ABSTRACT

The ability to quantify differences in walking balance proficiency is critical to curbing the rising health and financial costs of falls. Current laboratory-based approaches typically focus on successful recovery of balance while clinical instruments often pose little difficulty for all but the most impaired patients. Rarely do they test motor behaviors of sufficient difficulty to evoke failures in balance control limiting their ability to quantify balance proficiency. Our objective was to test whether a simple beam-walking task could quantify differences in walking balance proficiency across a range of sensorimotor abilities. Ten experts, ten novices, and five individuals with transtibial limb loss performed six walking trials across three different width beams. Walking balance proficiency was quantified as the ratio of distance walked to total possible distance. Balance proficiency was not significantly different between cohorts on the wide-beam, but clear differences between cohorts on the mid and narrow-beams were identified. Experts walked a greater distance than novices on the mid-beam (average of 3.63 ± 0.04 m verus 2.70 ± 0.21 m out of 3.66 m; $p = 0.009$), and novices walked further than amputees (1.52 ± 0.20 m; $p = 0.03$). Amputees were unable to walk on the narrow-beam, while experts walked further (3.07 ± 0.14 m) than novices (1.55 ± 0.26 m; $p = 0.0005$). A simple beam-walking task and an easily collected measure of distance traveled detected differences in walking balance proficiency across sensorimotor abilities. This approach provides a means to safely study and evaluate successes and failures in walking balance in the clinic or lab. It may prove useful in identifying mechanisms underlying falls versus fall recoveries.

1. Introduction

There is an urgent need for a quick, simple, and low-cost physical performance measure that can detect differences in balance performance over a broad range of sensorimotor abilities; from individuals with motor impairment to elite athletes recovering from a concussion [1]. Balance ability while walking is a critical factor in determining quality of life [2] yet it is especially difficult to assess. Currently there is no accepted laboratory-based approach to evaluate and study balance ability during walking [3]. Moreover there are no specific tests that reliably assess walking balance impairment or fall risk in a clinical setting [4]. These gaps may be attributable to the scarcity of easily implemented clinically feasible techniques, metrics, and analyses that probe for and quantify failures in human balance performance [5,6]. This limits the identification of neuromechanical principles that govern better walking balance and the determination of fall risk in patients.

Current laboratory-based biomechanical approaches used to study walking balance typically focus on movements or measures during successful performance. Many laboratory studies characterize the challenge to balance control during walking [7], the strategies used to maintain balance while walking [8], or the strategies used to restore balance after a perturbation to walking [5,9,10]. However, the relationship between these strategies or metrics to balance proficiency is unclear.

Clinical balance instruments such as the Berg Balance Scale, the Activities-specific Balance Confidence Scale, the Fullerton Advanced Balance Scale, and the Dynamic Gait Index require little in the way of specialized equipment and are relatively quick and inexpensive to administer. Yet they are not without their limitations. Many of these tools provide a nonspecific evaluation of balance rather than an assessment that specifically targets walking, the behavior when most falls occur [11]. For example they often pool static and dynamic [12], as well as standing and walking

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[13] balance tasks. However, there is little correlation between such elements [9,14]. Many of these clinical balance tests show ceiling effects and are usually not sensitive enough to small improvements or decreases in balance ability [15].

The inability of laboratory and clinically based measures to quantify balance proficiency may stem from the use of motor behaviors that are of insufficient difficulty to evoke failures in balance control. If successful balance is defined by the absence of falls [16] then experimental conditions should be of sufficient difficulty to result in a loss of balance. Without conditions that allow for the identification of failures establishing the proficiency with which someone can maintain their balance is speculative. It depends on previously established statistical relationships between a given metric and a self-reported history of falls [17] rather than a direct assessment of walking balance proficiency.

Beam walking has been used to examine the effects of age [14,18] on walking balance, as well as physical guidance and error augmentation on motor learning [19]. More recently beam walking has been used in attempts to identify cortical events that precede a loss of balance [20]. However its capacity to differentiate levels of walking balance proficiency across a range of sensorimotor abilities and specifically individuals with mild balance impairment remains unknown. Therefore the objective of this study was to test whether a simple and low-cost beam-walking task along with an easily interpreted metric could discriminate across the spectrum of walking balance proficiency (i.e. expert to impaired). Beam walking (Fig. 1) presents a challenge to balance control and provides a simple and stringent assessment of balance failures; individuals are either on or off the beam.

2. Methods

2.1. Participant recruitment

Three cohorts of participants were recruited: trained experts (professionally trained ballet dancers), untrained novices, and individuals with unilateral transtibial limb loss (TTLL). Individuals with traumatic TTLL were chosen because of their mild balance impairments that are traditionally difficult to detect with conventional balance assessments. For all participants' inclusion criteria were age greater than 18 years. Inclusion criteria for individuals with TTLL included: time since limb loss greater than one year, cause of limb loss non-dysvascular, at least 8 h of prosthesis wear per day, and self-reported ability to ambulate with variable cadence. Inclusion criteria for trained experts included a minimum of 10 years of ballet training, while untrained novices were required to have no previous history of formal dance or gymnastic training. Exclusion criteria were medical conditions assessed by self-report which could result in impaired balance or sensory loss. This could include significant musculoskeletal, neurologic, or cardiopulmonary conditions, but not limb loss for the cohort of individuals with TTLL. While aging has been shown to affect beam-walking performance, most evidence suggests that this does not occur until 70 years of age [14,18]. Therefore potential participants over the age of 70 were excluded. Institutional Review Boards of Georgia Tech and Emory University approved all protocols. Written informed consent was obtained from each participant prior to enrolment.

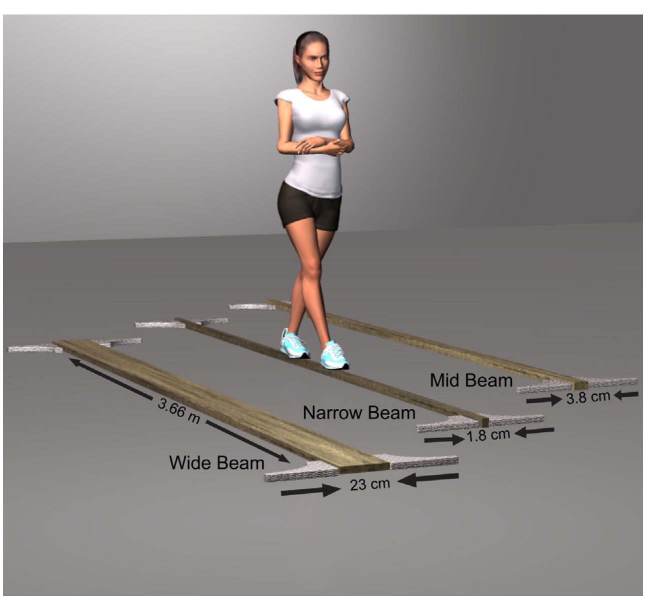

Fig. 1. Experimental beam walking paradigm. Participants attempted six walking trials across three beams in a heel-to-toe gait pattern with their arms crossed over their chest. If participants moved their arms or stepped off the beam (i.e. balance failure) the trial was terminated and the distance walked was recorded. Each beam was 3.66 m (12 ft) long, but varied in width, wide: 23 cm, mid: 3.8 cm, and narrow: 1.8 cm.

2.2. Experimental apparatus

Three 3.66-m long beams (12 ft) of varying widths were used: a wide beam (23 cm), a mid-width beam (3.8 cm), and a narrow beam (1.8 cm) (Fig. 1). The wide beam was selected to impose minimal challenge to balance control, as the medial–lateral base of support beneath the stance foot was no different than that experienced in single-limb stance during overground walking. The mid and narrow width beams were chosen based on previous research [14,19] and feasibility testing such that they would provide progressively greater challenge to medial–lateral balance control and evoke balance failures across cohorts. In an effort to minimize the effect of postural threat [21] on walking balance performance the height of each beam was kept low (wide-beam: 1.75 cm, mid-beam: 3.25 cm, narrow-beam 3.25 cm).

2.3. Experimental protocol

Each participant attempted six walking trials across each of the three beams. The order in which each beam was tested was randomized across participants. For each trial participants were instructed to keep their arms crossed over their chest and walk in a heel-to-toe pattern (Fig. 1). While arms may play a major role in maintaining walking balance this constraint was imposed to avoid potential confounds that could arise from the use of different arm strategies between participants. A prescribed step length was not enforced as previous work demonstrated that it has little effect of beam walking performance [14]. All participants wore standardized shoes. A successful trial was one in which participants traveled the length of the beam without stepping off (i.e. a loss of balance) and without moving there arms from a fixed position across their chest. Anything else was considered a balance failure. Once a balance failure was observed during a trial that trial and the collection of walking distance was stopped.

2.4. Data collection, processing and analysis

Three-dimensional marker coordinate data of a single reflective marker placed on the seventh cervical vertebrae (C7) were collected at 120 Hz using an eight-camera motion capture system (Vicon, Centennial, CO). Walking balance proficiency was quantified using filtered C7 marker coordinate data (third-order 30 Hz low-pass Butterworth filter) to calculate the normalized distance walked on each beam. The normalized distance walked was