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

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A B S T R A C T

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.

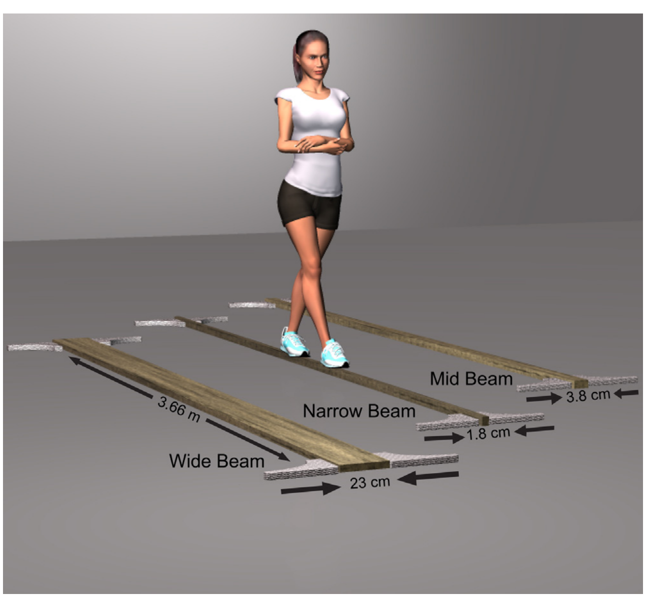

Fig. 1. Experimental beam walking paradigm. Participants attempted six walking trials across three beams in a heel-to-toe gait pattern with their arms crossed over their chest. If participants moved their arms or stepped off the beam (i.e. balance failure) the trial was terminated and the distance walked 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 calculated as the quotient of the sum of the distances traveled over all six trials and the maximum possible distance (i.e. six trials × 3.68 m/trial = 22.08 m). A participant who is successful on all six trials for a given beam would have a normalized distance walked of 1.0.

2.5. Statistical analysis

To determine the effect of group (expert, novice, and TTLL) on normalized distance walked for each beam condition (wide, mid, narrow) a 1-way ANOVA was performed for each beam width. The level of significance was set at $\alpha = 0.05$. A Games-Howell test was used for post hoc testing to account for unequal variance and sample sizes. To test for a learning effect repeated measures ANOVA were performed using the first, third and sixth trials for the mid- and narrow-width beams. When assumptions of sphericity were not met a Greenhouse–Geisser adjustment was used. All statistical tests were conducted using SPSS (V.21; SPSS, Inc., Chicago, IL).

3. Results

Ten experts (professional ballet dancers), 10 untrained novices, and five individuals with unilateral TTLL participated in the study (Table 1). Balance proficiency was visually (Supplementary files A–C) and quantitatively (Fig. 2) different between cohorts. Significant differences were identified between cohorts in the normalized distance walked on the narrow ($p < 0.0005$) and mid beams ($p < 0.0005$), but not the wide beam ($p > 0.05$). Post hoc testing revealed that on the mid and narrow beams experts walked significantly further than novices (mid beam: $p = 0.009$; narrow beam: $p = 0.0005$), or individuals with unilateral TTLL (mid beam: $p = 0.004$; narrow beam: $p < 0.0005$), while novices walked further than individuals with TTLL (mid beam: $p = 0.03$; narrow beam: $p = 0.0005$) (Fig. 2). There were no significant differences in the normalized distance walked on the mid or narrow beams between the first, third trials, and sixth trials ($p > 0.05$) for all cohorts (Fig. 3). Importantly, there were no falls during testing demonstrating the safety of the test.

4. Discussion

The assessment of walking balance proficiency remains a challenge. Here we demonstrated that a simple low-cost beam-walking task and a basic measure of distance walked could detect differences in walking balance proficiency across a broad range of sensorimotor abilities. While additional work is necessary to determine whether beam walking is capable of classifying fallers from non-fallers and predicting the likelihood of a fall, the identification of clinical and experimental methods that can accurately quantify differences in walking balance performance across the spectrum of sensorimotor ability represents an important step in addressing the continued rise of health and financial costs associated with falls [22]. This is particularly the case among individuals with mild (aging) or transient (i.e. concussion) sensorimotor impairment that are traditionally difficult to detect with standard balance assessments.

A feature of the proposed beam walking tasks is the potential to assess a broad range of balance abilities using gradations of the same test. There are few balance assessment tools to study diverse skill levels, as very different tests are typically required to evaluate cohorts of different capabilities. Popular clinical instruments such as the Berg Balance Scale and Dynamic Gait Index often have a ceiling effect [23,24]. This limits their ability to detect mild balance

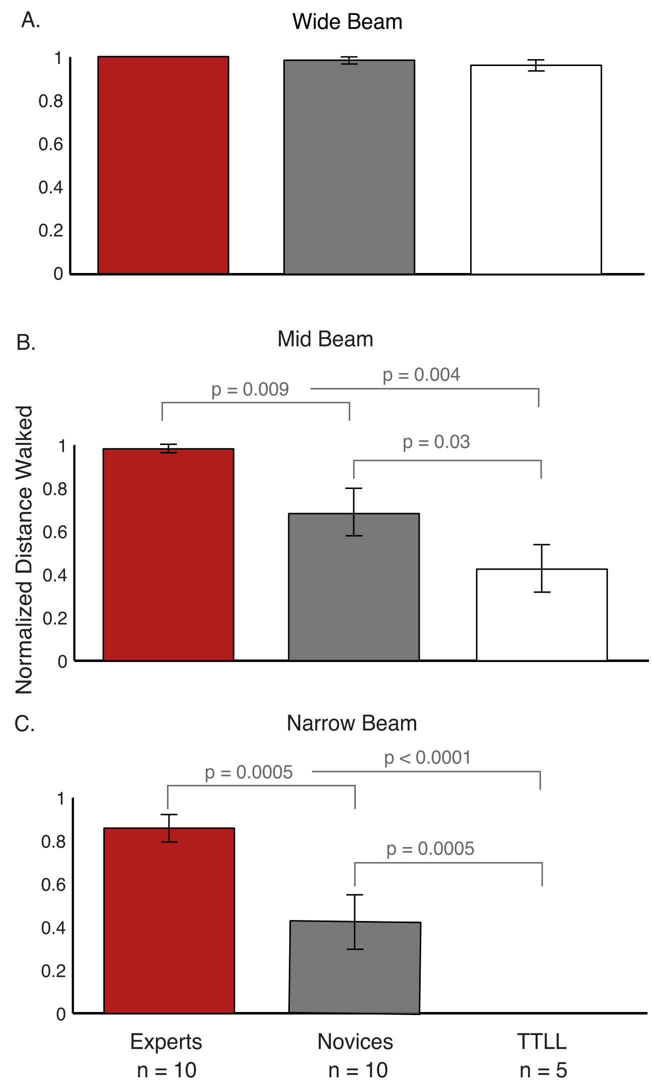

Fig. 2. Average beam walking proficiency. (A) The average normalized distance walked over six trials was not significantly different between experts (red), novices (gray) and individuals with transtibial limb loss (white) on the wide beam, but was significantly different on both the (B) mid and (C) narrow width beams. On the mid and narrow width beams, the experts walked a greater average distance than either the novices or individuals with TTLL, while the novices outperformed the individuals with TTLL on both beams. Individuals with TTLL were unable to perform the narrow beam condition. TTLL = transtibial limb loss. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Participant demographics.

Cohort		Height (m)	Mass (kg)	Age (years)	Gender	Time since limb loss	Cause of limb loss
Trained experts ($n = 10$)	Mean (*SD*)	1.63 (*0.05*)	53.79 (*6.73*)	22 (*2*)	10 F	N/A	N/A
	Range	1.57–1.72	46.90–66.20	19–25			
Untrained novices ($n = 10$)	Mean (*SD*)	1.66 (*0.05*)	64.76 (*9.61*)	22 (*3*)	10 F	N/A	N/A
	Range	1.59–1.73	53.40–83.70	19–30			
Individuals with transtibial limb loss ($n = 5$)	Mean (*SD*)	1.73 (*0.09*)	76.92 (*12.41*)	45 (*13*)	5 M	8.3 (*5.3*)	Trauma
	Range	1.63–1.83	64.10–94.20	26–63		4–18	

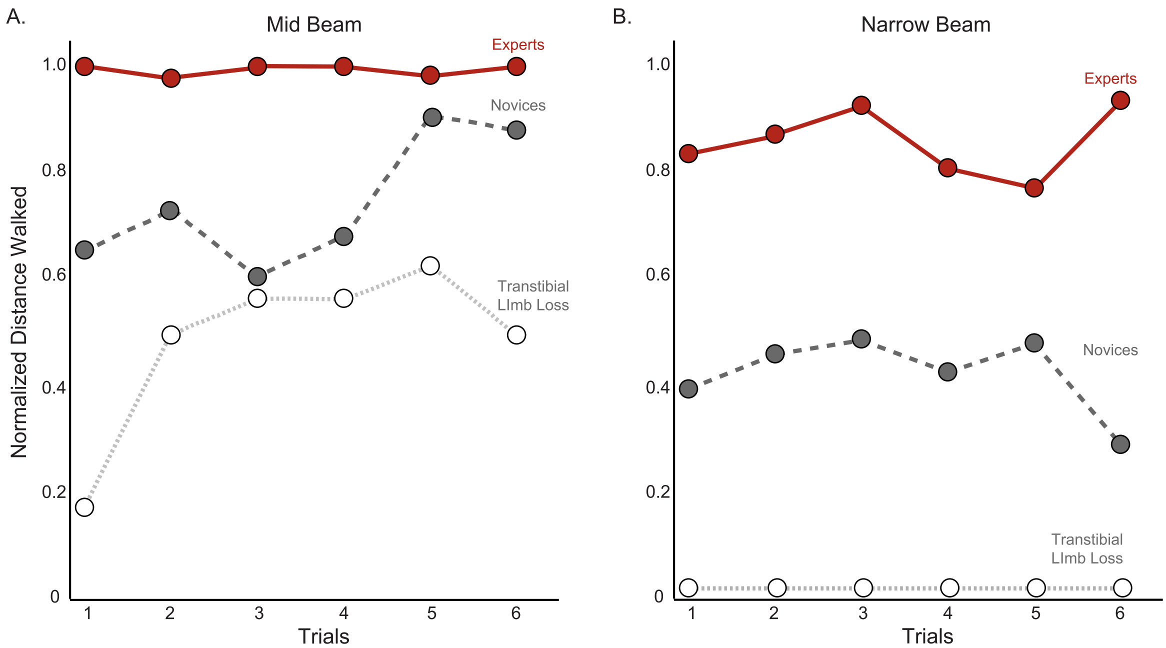

Fig. 3. Trial-by-trial beam walking proficiency. No significant learning effect was detected for any of the cohorts between the first, third and sixth trials on either the mid or narrow width beam. This suggests that repetition over six trials may contribute to accuracy but not learning.

impairments and constrains their use to a narrow range of more severely affected patients. The use of a common motor test may serve to facilitate the comparison of walking balance proficiency across diverse patient populations. With additional work beam walking could become a quick, simple, and low-cost physical performance measure of walking balance proficiency that is suitable for clinical and research purposes.

Tests like the narrow beam condition that provide considerable challenge to balance control may prove useful in the assessment of higher functioning individuals and attempts to identify the upper limits of human balance performance. For example the narrow beam walking test may be useful in testing injured athletes where balance deficits such as those related to concussion are difficult to detect. In contrast walking balance tests of moderate difficulty, such as the mid beam condition, may be more appropriate for detecting differences in walking balance proficiency [14] owing to mild sensorimotor deficits that would not be revealed by standard balance assessments.

Tests of minimal difficulty such as the wide beam condition may be useful for assessing individuals with more profound sensorimotor deficits. For example a single individual with unilateral transfemoral limb loss was found to have considerable difficulty avoiding failures on the wide beam (Supplementary file D). The medial–lateral base of support beneath the feet during wide beam walking is equivalent to that of overground heel-to-toe tandem gait. This is a task that is routinely included in neurological examinations as an overall indicator of walking balance [25], as well as some clinical balance instruments [13]. However conditions such as tandem-walking that do not reduce the medial–lateral base of support beneath the feet are unlikely to evoke balance control failures in all but the most impaired individuals, limiting their utility in clinical testing [14] and research. The degree to which wide beam and overground tandem walking are equivalent is unknown. It is possible the wide beam condition is more challenging than tandem walking due to the slight elevation of the beam and explicit limits on lateral stepping.

Beam walking may be a clinically feasible way to rapidly assess walking balance proficiency. Much like many popular clinical tools for testing walking balance beam walking requires minimal time, expertise, and expense to implement. Beam walking may even be quicker and less expensive than some clinical measures depending on their cost and time to administer. Although a motion-capture system was used in the present study the same measure of walking balance proficiency, distance traveled, could also be acquired using a tape measure. Prior to clinical implementation issues related to the selection of beam width, the necessary number of trials, metric sensitivity to variations of sensorimotor impairment, and validation with existing assessment tools must first be addressed. The use of a single beam would greatly expedite the required testing time, as would the identification of the minimum number of trials for a valid and reliable assessment. The preliminary results presented here (Fig. 3) suggest that performing three trials and selecting the best performance from among those three might provide a reasonable measure of walking balance proficiency in a minimal amount of time. It is also possible that the inclusion of alternative or secondary metrics such as movement smoothness or beam walking velocity may help to further discriminate within levels of expertise and impairment. Lastly a thorough validation and comparison of beam walking to standard assessment tools is needed, particularly between fallers and non-fallers.

In addition to its potential clinical utility beam walking could be used to clarify the interpretation of current laboratory-based biomechanical measures of walking balance and to identify mechanisms of balance failures versus success. For example, previous work has reported both an increase [26] and a decrease [27] in step-to-step variability among fall prone subjects. Similarly, popular measures of CoM–CoP dynamics such as extrapolated CoM and its margin of stability [7] have been reported to increase [28] and decrease [29] in the prosthetic leg of lower limb amputees. As a result such measures can be difficult to interpret and provide little consensus regarding what constitutes better walking balance. It is also unclear to what degree these measures are directly related to walking balance proficiency [30] as they have yet to be examined under conditions that allow for failures in balance control. During beam walking participants are either on or off the beam and the distance they travel on the beam directly reflects their balance proficiency. Traditional laboratory-based biomechanical measures could be calculated during beam walking to examine their relationship to walking balance proficiency on the beam. Furthermore, overground values of these same biomechanical measures could be correlated to beam walking performance in order to determine their ability to predict walking balance proficiency on the beam. Such examinations may resolve existing uncertainty in the role and interpretation of common laboratory-based biomechanical measures of walking balance. Such analyses will likely reveal that these biomechanical measures are a reflection of the possible strategies that can be employed to maintain or restore balance while walking rather than direct measures of walking balance proficiency. As a laboratory-based tool beam walking provides a simple and relatively safe way to elicit failures in balance control during walking as evidenced by the absence of falls during testing. Therefore, beam walking may be of use in identifying and understanding the underlying strategies and mechanisms of balance failures versus successes. This line of inquiry may result in novel findings that provide a neuromuscular basis for improvements in standing and walking balance that could be applied to a broad range of patient populations.

Here we have provided evidence that a simple beam-walking task combined with an easily collected measure of distance traveled can detect differences in walking balance proficiency between experts, novices, and individuals with sensorimotor impairment. This approach provides a means to safely probe and study successes and failures in walking balance in the clinic or lab. It may prove useful in identifying strategies and mechanisms that drive better walking balance (i.e. successes versus failures), while providing clinicians with a simple and direct way of assessing balance impairment and fall risk in patients.

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Conflict of interest statement

The authors attest to having no conflict of interest regarding this work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2015.01.007.

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