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A study to assess whether fixed-width beam walking provides sufficient challenge to assess balance ability across lower limb prosthesis users

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Abstract

Objective: To evaluate the feasibility of fixed-width beam walking for assessing balance in lower limb prosthesis users.

Design: Cross-sectional.

Setting: Laboratory.

Subjects: Lower limb prosthesis users.

Methods: Participants attempted 10 walking trials on three fixed-width beams (18.6, 8.60, and 4.01 wide; 5.5 m long; 3.8 cm high).

Main measures: Beam-walking performance was quantified using the distance walked to balance failure. Heuristic rules applied to each participant's beam-walking distance to classify each beam as "too easy," "too hard," or "appropriately challenging" and determine whether any single beam provided an appropriate challenge to all participants. The number of trials needed to achieve stable beam-walking performance was quantified for appropriately challenging beams by identifying the last inflection point in the slope of each participant's trial-by-trial cumulative performance record.

Results: In all, 30 unilateral lower limb prosthesis users participated in the study. Each of the fixed-width beams was either too easy or too hard for at least 33% of the sample. Thus, no single beam was appropriately challenging for all participants. Beam-walking performance was stable by trial 8 for all participants and by trial 6 for 90% of participants. There was no significant difference in the number of trials needed to achieve stable performance among beams ($P = 0.74$).

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Declaration of Conflicting Interests

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Conclusion: Results suggest that a clinical beam-walking test would require multiple beams to evaluate balance across a range of lower limb prosthesis users, emphasizing the need for adaptive or progressively challenging balance tests. While the administrative burden of a multiple-beam balance test may limit clinical feasibility, alternatives to ease this administrative burden are proposed.

Keywords

Postural balance; falls; amputee; rehabilitation; walking

Introduction

Contemporary clinical balance tests are often too easy for lower limb prosthesis users and do not pose sufficient physical challenge to expose subtle, but critically important, differences in balance that underlie fall risk.[1] These tests often exhibit ceiling effects,[1] fail to identify those with a fall history,[1,2] or cannot detect clinically important changes in balance. There is therefore a need for clinical tests that pose greater challenge to balance[1,3–5] and accommodate a broader range of balance abilities (i.e. varying levels of impairment).

Beam walking represents a possible approach to balance assessment that could achieve these goals.[4,6] Walking along a low, raised beam challenges control of lateral motions[7] by constraining step width. Beam-walking performance also appears to differentiate between groups with known differences in balance ability. This includes younger and older adults,[6,8] controls and lower limb prosthesis users,[4] as well as ballet and nonballet dancers.[4]

Use of beam walking as a clinical balance test is currently limited by a lack of knowledge regarding the beam widths, the number of beams, and the number of trials that are needed to evaluate people with different balance abilities. There is currently no consensus as to whether one fixed-width beam[4,6,8,9] provides appropriate challenge to all individuals or multiple beams[6,9] are needed to accommodate different levels of impairment. Additionally, while preliminary beam-walking evidence suggests minimal learning effects,[4] trial-to-trial variations[9] indicate possible learning effects. However, an insufficient number of trials have been administered to ascertain whether and when participants' beam-walking performance stabilizes.

The objective of this study was to evaluate the feasibility of fixed-width beam walking for assessing balance in lower limb prosthesis users. First, we determined whether a single fixed-width beam could provide an appropriate challenge to users. Second, we identified the number of trials required to achieve stable beam-walking performance. We predicted that no single fixed-width beam would provide adequate challenge to all users and that users' beam-walking performance would stabilize within 10 trials. Results of this study will help determine whether beam walking can be a feasible clinical balance test and contribute knowledge toward a beam-walking test protocol.

Methods

A cross-sectional study of balance ability in lower limb prosthesis users was conducted between July 2016 and April 2017. A University of Illinois at Chicago Institutional Review Board reviewed and approved all study protocols. Each participant provided written informed consent prior to enrollment.

Participants were recruited from local prosthetic clinics. Inclusion criteria were (1) 18 years of age or older; (2) unilateral, transtibial, or transfemoral amputation; (3) use of a prosthesis for 1 year or more; (4) use of a prosthesis to ambulate; and (5) able to walk at least 3 m over level terrain without an assistive device (e.g. cane). Exclusion criteria were (1) amputation of another limb, (2) contralateral complications (e.g. hip replacement), (3) ulcers or infections associated with compromised circulation of the contralateral leg, (4) advanced neurologic disorders, or (5) congestive heart failure or obstructive pulmonary disease.

Demographic and health-related information were collected from participants prior to testing. Demographic characteristics including age, height, weight, and sex were obtained via self-report. Health-related information including level of amputation, cause of amputation, time since amputation, prosthetic prescription, and time with current prosthetic prescription were obtained via interview. Each participant's Medicare Functional Classification Level[10] was determined through clinical inspection and interview by an experienced prosthetist. Finally, participants' perceived mobility was determined using the Prosthetic Limb Users Survey of Mobility (PLUS-M) 12-item short form. PLUS-M has exhibited strong evidence of reliability and validity in lower limb prosthesis users and is advocated for use in clinical and research settings.[11,12]

Three fixed-width beams (5.5 m long) were constructed for testing (Figure 1). Beam heights were low (3.8 cm high) to minimize postural threat.[13] Braces were affixed to the lateral edges to restrict beam movement. Width varied by beam (wide = 18.6 cm, intermediate = 8.60 cm, and narrow = 4.01 cm) to create increasingly challenging walking conditions. Beam dimensions were based on previous research that included young unimpaired adults,[14] older adults,[6] lower limb prosthesis users,[4] and professional ballet dancers.[4] These studies demonstrated that these widths challenged individuals with a range of balance abilities. Lines were placed every 6 in. along the length of each beam to facilitate scoring.

Each participant attempted 10 walking trials on each beam. Beam conditions (i.e. widths) were presented in random order, but participants were required to attempt all 10 trials before continuing to the next condition. Participants began each trial with one foot on the beam and the other on the ground to the side. Participants were instructed to walk along the beams with their arms crossed over their chest. Arm position was constrained to mitigate potential differences in upper limb compensation strategies across subjects. Step length was not instructed, as prior research demonstrated that such instructions have little effect on participants' beam-walking performance.[6] A balance failure was recorded if a participant stepped off the beam or uncrossed their arms before walking the beam length. The most anterior position of the last foot on the beam when the balance failure occurred was recorded

as the distance walked along the beam. Participants were allowed to rest as needed between conditions. All participants wore their own footwear.

Beam-walking performance was quantified for each trial using the "normalized distance," the distance walked to balance failure relative to overall beam length.[4] Because participants started the test with one foot on the beam, normalized distance was calculated relative to the final 4.9 m of each beam. By quantifying performance relative to the 0.6 m mark, we ensured participants placed at least one additional foot on the beam before measurement was initiated. Normalized distance was therefore 0.0 if the participant did not exceed the 0.6 m mark on a given trial and 1.0 if the participant walked the entire length of the beam. If the participant stepped off the beam after 1.8 m (i.e. 1.2 m past the starting line), normalized distance was calculated as 0.24 m (1.2 m/4.9 m).

The feasibility of beam walking as a clinical balance test was evaluated based on whether a single fixed-width beam could provide an appropriate level of challenge to all participants. A single fixed-width beam would minimize the administrative burden (i.e. number of test conditions and time) and limit the equipment (i.e. beams) required to test a range of individuals. To determine whether such an approach was possible, we developed heuristic rules to indicate whether each beam was "too easy," "too hard," or "appropriately challenging" for each participant. Specifically, if a participant demonstrated the minimum level of performance (normalized distance = 0.0) in three or more trials on a single beam, it was considered too hard (i.e. the participant could not consistently start the test). Similarly, if the participant demonstrated the maximum level of performance (normalized distance = 1.0) in three or more trials, the beam was determined to be too easy (i.e. the participant regularly finished the test). If the participant demonstrated an interim level of performance (i.e. fewer than three trials at maximum or minimum performance), then the beam was determined to be appropriately challenging (i.e. the participant was regularly able to start the test but not complete it). Three trials were selected as a threshold based upon initial visual inspection of the data. This approach was similar to that used previously to identify appropriately challenging conditions in a narrow beam stance test.[15]

We applied the above rules to each participant's beam-walking results (i.e. normalized distance from all 10 trials on each beam) to determine the percent of participants who were appropriately challenged by each beam. As an initial goal, we determined whether at least 85% of the sample could be appropriately challenged with any one of the beams. Minimal or maximal performance on a health status instrument by 15%–20% of a sample is considered evidence of floor and/or ceiling effects.[16,17] We considered it likely that a test based on a single fixed-width beam would exhibit floor or ceiling effects if was too easy or too hard for 15% or more of this study sample. Using the same rules, we also determined whether each participant had at least one beam that provided an appropriate challenge. If results showed that a single beam was not appropriately challenging for all participants, but that each participant had a least one beam that provided an appropriate challenge, a multiplebeam clinical test could be used to assess a range of lower limb prosthesis users.

We also sought to determine whether and when participants' beam-walking performance stabilized on an appropriately challenging beam(s). To assess stabilization, we used a

recursive algorithm to identify significant changes in the slope of each participant's trial-by-trial cumulative beam-walking performance record.[18] The recursive algorithm identifies a series of candidate "change points" or trials where performance deviates maximally from a line connecting the first trial and each subsequent trial. The strength of evidence that each candidate change point is a true change point is calculated as the log of the odds (i.e. logit) that there is no change in performance. The algorithm then selects the first candidate change point that exceeds the specified logit threshold (selected here as two, which is equivalent to an alpha value of 0.01) and truncates the record at that trial. The algorithm repeats this process to identify any subsequent change points in the remaining record.

The last change point identified by the algorithm denotes the trial where a participant's performance reaches a terminal slope (Figure 2). Trials that occur after the last change point therefore reflect a period of stable performance. For example, beam-walking performance of a participant whose last change point occurred at trial 4 would be considered stable from trials 5 to 10 (Figure 2). However, if the last change point occurred at trial 9, the participant would not be considered to have archived stable beam-walking performance. This analysis was applied to the trials of those participants who found a given beam width appropriately challenging.

To determine whether the trial where participants' performance stabilized differed by beam condition, we compared last change points across beams using an analysis of variance or a Kruskal-Wallis test. A Shapiro-Wilk's test was used to assess the normality of the distribution of last change points and determine use of the appropriate parametric or non-parametric test. Change point analysis was performed with MATLAB R2017a (MathWorks, Inc., Natick, MA, USA) using published routines,[19] and other statistical tests were conducted with SPSS 24 (SPSS, Inc., Chicago, IL, USA).

Results

In all, 30 people were recruited to participate in the study (Table 1). An equal number of participants were male and female (n = 15 each). Participants were distributed across the range of Medicare Functional Classification Levels (n = 1 K1, n = 11 K2, n = 13 K3, and n = 5 K4). More than half of the participants had a transtibial amputation (n = 19); fewer had transfemoral amputation (n = 11). Participants' amputation was due to a variety of causes, including trauma (n = 19), dysvascular disease (n = 7), and cancer (n = 4). Descriptive statistics summarizing the normalized distances walked by each participant are reported in Supplementary Table 1.

No single fixed-width beam provided an appropriate challenge for assessing balance among all participants in our sample. Each of the fixed-width beams was found to be either too easy or too hard (as defined previously) for at least one-third of the sample (Figure 3). More than 80% of the participants registered three or more trials at *maximum* performance (i.e. too easy) on the wide beam, while only 39% of the study sample found the intermediate beam to be too easy. In contrast, only 30% of the participants registered three or more trials at the *minimum* level of performance (i.e. too hard) on the narrow beam.

While no single fixed-width beam provided an appropriate challenge to all participants, each participant had at least one beam that was appropriately challenging to assess his or her balance ability. The normalized distances walked (mean, median, range) across beams deemed appropriately challenging for participants was wide: 0.19, 0.17, and 0.06–0.69; intermediate: 0.23, 0.20, and 0.04–0.51; and narrow: 0.27, 0.25, and 0.09–0.53 (Supplementary Table 1). Overall, normalized distance walked on appropriately challenging beams was greater than 0.0 but less than 1.0 in more than 90% of trials. In contrast, normalized distance walked on beams deemed too easy or too hard was greater than 0.0 but less than 1.0 in only 10%–40% of trials (Table 2).

Beam-walking performance stabilized for each participant on beams that were deemed to be appropriately challenging. The last change point was not normally distributed for the intermediate ($P = 0.001$), narrow ($P = 0.001$), or wide beams ($P = 0.012$). A Kruskal-Wallis test determined that the point of stable performance (i.e. median last change point) was not significantly different between beam conditions (median, interquartile range (IQR); wide: 3.0 and 4.8; intermediate: 2.0 and 4.0, narrow: 1.0 and 3.0, $H(2) = 0.603$, $P=0.74$). Across beams, all participants demonstrated stable performance during trials 9–10 for appropriately challenging beams (Figure 4). However, more than 90% of participants exhibited stable performance during trials 7–10 (i.e. last change point at trial 6).

Discussion

The results of this study revealed that at least one-third of participants found each fixed-width beam to be either too easy (i.e. they could walk the entire length of the beam without a balance failure) or too hard (i.e. they experienced a balance failure as soon as they began walking). However, each participant was found to have at least one beam that provided an appropriate challenge (i.e. they could routinely start but not finish the beam-walking task). On beams deemed to be appropriately challenging, walking performance stabilized for all participants by trial 8 and by trial 6 for a majority of participants. These results suggest that beam walking could be used as a clinical test to evaluate balance ability across a range of ambulatory lower limb prosthesis users, but would require multiple beams to avoid ceiling and floor effects. While a multiple beam test may limit immediate clinical feasibility, alternatives are proposed to ease administrative burden.

Walking on a single fixed-width beam is not a clinically feasible method for evaluating balance ability across a range of lower limb prosthesis users. At least one-third of participants found each beam too easy or too hard (Figure 3(a)). Given the 15%–20% sample threshold generally referenced as evidence of floor and/or ceiling effects,[16,17] results suggest that a clinical test derived from a single, fixed-width beam would exhibit poor content validity. Although no single fixed-width beam was appropriate for all study participants, at least one of the three beams appropriately challenged each participant. This indicates that multiple, fixed-width beams are needed to assess a range of lower limb prosthesis users. This finding is consistent with previous beam and narrow path walking research. Specifically, a set of four fixed-width beams was found to be more discriminating of age-related balance ability than any single beam.[6] Similarly, multiple widths are generally required to perform the narrowpath walking test.[3,20] Importantly, performance on

appropriately challenging beams was often, but not always, between 0.0 and 1.0 (Table 2). This suggests that the heuristic three-trial rule developed in this study could be integrated into a clinical protocol for administering a multiple-beam walking test.

A multiple-beam test offers several advantages over a single-beam test. For example, walking on beams of decreasing widths may reveal balance impairments better than less challenging tests.[5,19,21] Each beam in a multiple-beam test may also reveal different biomechanical determinants of balance control. For example, once a beam becomes narrower than someone's foot, the maximum ankle moment available for controlling lateral balance may be reduced,[6] necessitating the use of a hip strategy. Additionally, as beam width narrows from wide to intermediate, foot placement accuracy and precision may be challenged. A multiple-beam test could be used to facilitate understanding of the biomechanical requirements of beam walking[15,22] (i.e. what deficits make a given beam too easy, too hard, or appropriately challenging) and provide new knowledge about the underlying etiology of fall risk.

A disadvantage to a multiple-beam test is that it would require more time and equipment to administer than a single-beam test. With clinicians reporting administrative burden as a barrier to using clinical tests,[23–28] efficiency of a multiple-beam test should be investigated. For example, it may be possible to determine each individual's appropriate beam using demographic characteristics (e.g. age), health-related information (e.g. time since amputation), and/or self-reported balance (e.g. Activities-specific Balance Confidence Scale score).[29] Using these variables in an ordinal logistic regression model may predict which beam provides an optimal challenge without testing each beam. Such a strategy would still require all three fixed-width beams be available. The space required to store and set up multiple beams may limit viability in some settings.

An alternative to a multiple-beam test could be a "narrowing beam" where segments from each are merged into a single beam. The approach may create a task (i.e. walking along a narrowing beam) that almost everyone could start, but few could finish. Thus, floor and ceiling effects would be minimal. This concept is consistent with narrowing paths that have been used to evaluate adults with multiple sclerosis.[30] As many participants in that study performed near the test ceiling, narrowing the beam to 2 in. (5.1 cm) like in this study may provide greater challenge to a range of individuals. Further research examining the efficacy and diagnostic utility of a narrowing beam test is warranted.

The time course of performance stabilization should be considered when scoring physical performance tests. Challenging tasks such as beam and narrow-path walking are increasingly used to measure balance and assess fall risk.[3,4,6,14,15,19,31–34] However, whether or when performance stabilizes has received limited attention. It is subsequently unclear whether an individual's score based on initial trials represents typical or atypical (e.g. usual, best, or worst) ability. Sawers and Ting[4] reported that lower limb prosthesis users', professional ballet dancers', and controls' beam-walking performance did not vary significantly over six trials, suggesting that performance in any trial would represent typical performance. However, trial-to-trial differences may have been obscured by the small sample size, variations in performance among participants, or the group level analysis used to assess

beam-walking performance. In this study, beam-walking performance varied and only stabilized for all participants after seven trials. These results suggest that an individual's initial performance does not accurately characterize their typical performance. Furthermore, it was observed that the time course of stabilization in this study varied among participants (Figure 4). Thus, the number of trials required to achieve stable performance may not be consistent between individuals.

It is challenging to compare stabilization results obtained in this study to prior research, as previous beam and narrow-path walking results have been limited by order effects[6] or too few trials.[3,19,35,36] Still, these studies provide insight into the possibility that short-term learning may affect beam-walking results. For example, individuals post stroke improved their narrow path walking performance over two trials,[19] while adults with multiple sclerosis did so over three trials.[34] In neither case did participants' performance stabilize. In contrast, adults with multiple sclerosis walking on a narrowing path were relatively consistent across three trials.[30] This suggests that a test with a continually increasing challenge may measure an individual's typical performance more efficiently than a test with a fixed challenge.

The results obtained in this study may also provide a basis for developing a beam-walking scoring procedure. By identifying the point at which performance stabilizes, results over subsequent trials can be averaged to generate an *observed score* (i.e. best approximation of one's true ability). To reduce the burden associated with administering a large number of trials to confirm stability, an estimate of the observed score could be developed from systematic examination of trials or combinations of trials (e.g. max, min, average) that precede each individual's period of stable performance. Among clinical balance tests, these types of analyses are rare and the number of trials is generally not well justified.[37–40] For example, Kristensen et al.[38] found that Timed Up and Go performance among individuals with hip fractures stabilized after four trials but recommended scoring the best of the first three trials without considering the relationship of that trial's performance relative to participants' performance in trials 5 to 6.

Importantly, we consider *stable* rather than *best* performance to be more appropriate for evaluating balance, as it better characterizes an individual's typical ability. Measuring best performance may overestimate an individual's balance and underestimate his or her fall risk. An administration protocol similar to that devised by Ashendorf et al.[41] (i.e. which estimated performance based on the average of trials 3 to 5) is instead recommended to improve the clinical feasibility of a beam-walking test without compromising its accuracy. Therefore, the trials needed to achieve stable performance in this study should not be interpreted as the number required in a beam-walking test. Rather, they should be viewed as the point after which an observed score can be acquired and used to develop an abbreviated testing and scoring procedure.

Results of this study are limited in that they are based on data from lower limb prosthesis users. Findings pertaining to the widths of beams, number of beams, and number of trials needed to measure balance ability may not apply to other clinical populations (e.g. people with incomplete spinal cord injury and older adults). Results are also limited by the choice of beam dimensions. Beams were fabricated from materials readily available (i.e. typical

construction beams) and different dimensions (e.g. interim beam widths) may provide different results. Finally, as this study was cross-sectional in nature, we assessed only shortterm learning effects. Longitudinal studies will be needed to determine whether beam-walking performance is similar over different days.

Overall, the results of this study suggest that a clinical beam-walking test would require multiple fixed-width beams, which may impose administrative burden on clinicians. However, use of heuristic rules or predictive modeling to identify an individual's ideal beam or development of a single narrowing beam may enhance the clinical feasibility of a beam-walking test. Future work is needed to investigate these options, develop a scoring procedure, and assess the validity and reliability of the resulting test. Importantly, issues of task difficulty and performance stabilization studied here likely pertain to other physical performance tests. Results of this study may therefore guide development of new clinical tests or changes in the administration and interpretation of contemporary physical performance instruments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Clinical Messages

- Beam walking can be used to evaluate balance in lower limb prosthesis users, but requires multiple beams to measure a range of ability.
- Adaptive or progressively challenging tasks are needed to evaluate varying levels of ability in a single test.
- Heuristic beam-selection rules or a narrowing beam could ease administrative burden.

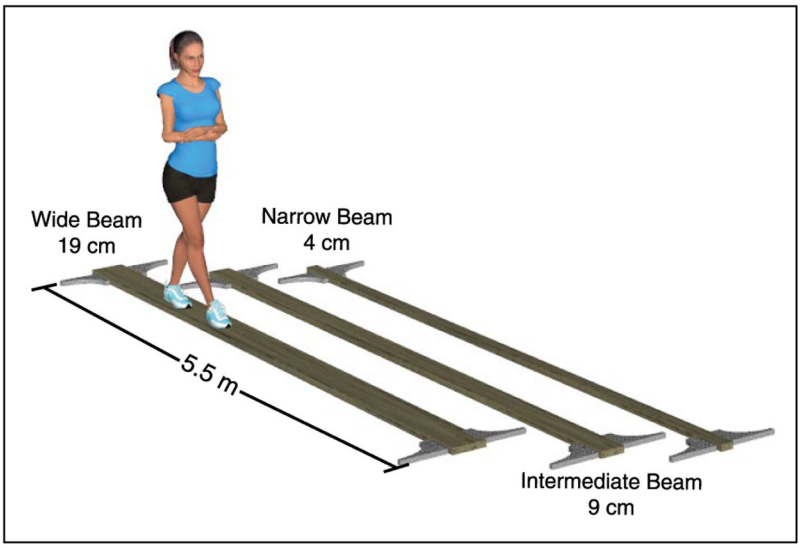

Figure 1.

The fixed-width beam-walking protocol. Participants attempted 10 walking trials across three fixed-width beams. Gait pattern was not constrained, but participants were asked to keep their arms crossed over their chest. If participants stepped off the beam or uncrossed their arms (i.e. balance failure), the trial was terminated and the distance walked to that point was recorded.

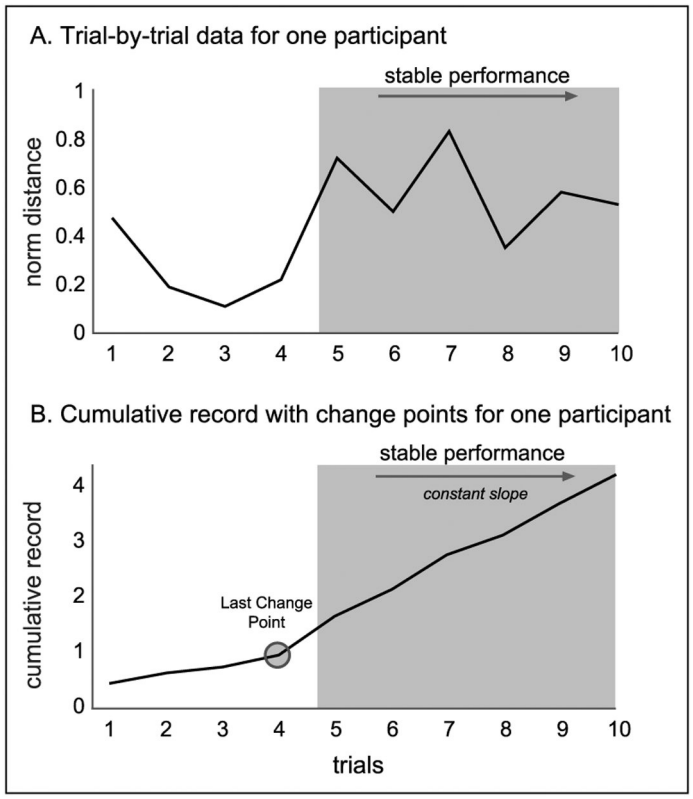

Figure 2.

Quantifying beam-walking performance stabilization. (a) Stable performance window (gray band) in a representative participant on the intermediate beam. (b) Stable performance windows were identified based on change points in the slope of the cumulative record of the normalized distance walked along each beam. For the same representative subject in (a), the last change point occurred during trial 4 (i.e. significant difference in slope before and after that trial).

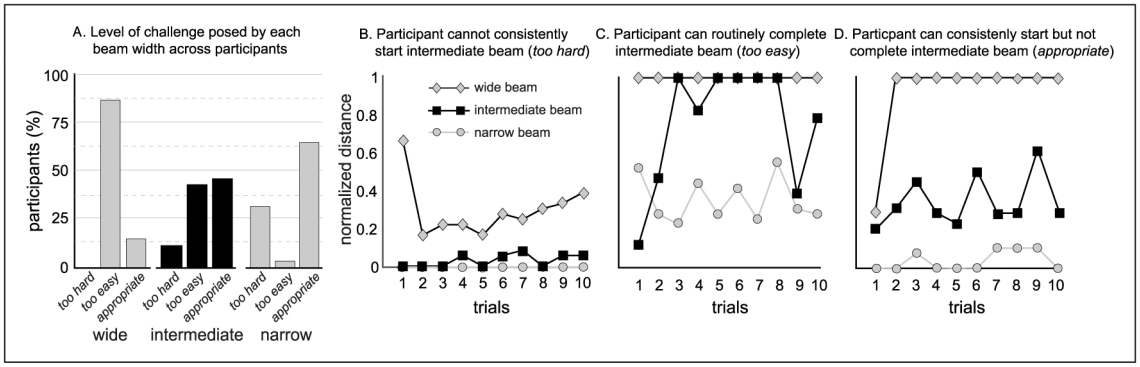

Figure 3.

No single fixed-width beam was found to provide an appropriate challenge for assessing balance across a broad sample of ambulatory lower limb prosthesis users. (a) Each beam tested in this study was deemed either too easy or too hard for at least one-third of the participants, suggesting that significant ceiling or floor effects may be present in a clinical test derived from a single fixed-width beam. Data from three individual participants show that the intermediate beam was deemed (b) too challenging for one, (c) too easy for a second, and (d) appropriate for a third. Similar results were observed for select participants on the wide and narrow beams.

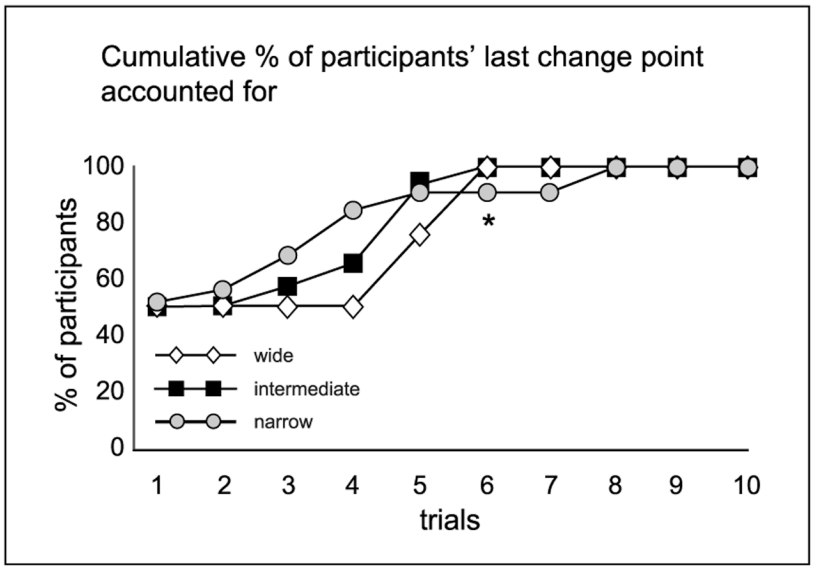

Figure 4.

Beam-walking performance stabilized for each participant. Eight trials were required to account for the last change point of each participant across all of the beam widths. However, over 90% of the participants' last change points occurred by trial 6 (asterisk).

Table 1.

Participant demographics.

	Age (years)	Height (cm)	Weight (kg)	Time since amputation (years)	PLUS-M (T-score)
Mean	46.97	173.74	78.74	13.66	53.05
SD	14.37	8.81	16.11	10.92	8.16
Range	24–69	154–188	47–107	2–40	37.1–71.4

SD: standard deviation; PLUS-M: Prosthetic Limb Users Survey of Mobility.

Table 2.

Mean number of trials on appropriate and inappropriate beams for which normalized distance was between 0.0 and 1.0.

	Wide (mean (SD))	Intermediate (mean (SD))	Narrow (mean (SD))
Appropriate	9.1 (0.6)	9.3 (0.7)	9.7 (1.0)
Inappropriate	1.4 (1.5)	4.1 (2.9)	1.2 (1.6)

SD: standard deviation.