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Development of an assessment of bilateral locomotor efficacy for individuals post-stroke

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ABSTRACT

Background: A common framework is needed to assess walking impairments in older adults and individuals with stroke. This study develops an Assessment of Bilateral Locomotor Efficacy (ABLE) that is a straightforward indicator of walking function.
Research question: Can we develop a clinically accessible index of walking function that summarizes gait dysfunction secondary to stroke?
Methods: The ABLE index was developed using a retrospective sample of 14 community-dwelling older adults. Data from 33 additional older adults and 105 individuals with chronic post-stroke hemiparesis were used to validate the index by factor analysis of the score components and correlation with multiple common assessments of lower extremity impairment and function.
Results: The ABLE consists of four components summed for a maximum possible score of 12. The components include self-selected walking speed (SSWS), speed change from SSWS to fastest speed, non-paretic leg step length change from SSWS to fastest speed, and peak paretic leg ankle power. The ABLE revealed good concurrent validity with all recorded functional assessments. Factor analysis suggested that the ABLE measures two factors: one for forward progression and another for speed adaptability.
Significance: The ABLE offers a straightforward, objective measure of walking function in adults, including individuals with chronic stroke. The index may also prove useful as a screening tool for subclinical pathology in community-dwelling older adults, but further testing is required. We encourage utilization of this index and reproduction of findings to adapt and refine the instrument for wider use and eventual clinical application.

1. Introduction

There is a need for a common framework to allow clinicians, researchers, and affected individuals to understand and rehabilitate walking function. The most widely used metric of walking function is habitual speed. Walking speed is valid and reliable, and data suggest that slow walking speed is an indicator of all-cause mortality in older adults [1,2]. Additionally, walking speed is an inexpensive, straightforward, and convenient measurement for use in various populations, often referenced as the 'sixth vital sign' or the 'functional vital sign' [3]. With all the touted benefits of walking speed as a metric comes a caveat: speed is influenced by a variety of factors. Two individuals who walk at the same speed can have different biomechanical patterns and levels of functional capacity [4]. Walking speed alone has also failed to predict response to rehabilitation or appropriate treatment prescription [5]. Our goal is to identify a measure of walking function that is more informative than walking speed alone but maintains the benefits of clinical accessibility and interpretability.

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There are several theoretical frameworks that describe the features of normal walking. In his 1989 text Inman suggested that there are two basic requisites of walking, continuous body support through ground reaction forces and periodic movement from one foot to another for progression [6]. Gage then broadened this idea into three "prerequisites for normal ambulation": stance stability; means of progression; and energy conservation [7]. Perry and Burnfield further expanded this framework to a fourth element, shock minimization during impact [8]. Each set of authors describes in detail the biomechanical characteristics that meet each of these requirements during gait. From these and other clinical and experimental observations, we can then build an understanding of which functions become impaired in pathological gait.

In the case of motor impairment secondary to a stroke, individuals experience predominantly one-sided weakness, or hemiparesis, typically resulting in a slower and more asymmetric gait relative to healthy individuals [9,10]. Perry proposed that individuals with stroke could be placed into one of six functional categories, which were intended to represent a clinical framework for developing treatment goals and give a reasonable prognosis for future walking capabilities [11]. These categories were not, however, intended to be absolute quantitative metrics of walking function. Some studies have adapted these categories and the associated sample demographics to form cutoffs and outcome measures for clinical trials, with limited success [5]. Others have assessed the ability of existing instruments like the Gait Deviation Index (GDI) and Gait Variability Index (GVI) to characterize individuals with stroke [12]. A quantitative approach rooted in theory and evidence of impairment that limits the capacity of individuals to walk normally is necessary to create a global index of locomotor function which is also inclusive of individuals post-stroke.

There are a variety of existing clinical and functional indices specifically designed to assess gait across healthy, aging, and pathologic populations. Some examples of the many indices used in research include the Dynamic Gait Index (DGI), GVI, and GDI. The DGI is an observational measure, while the GVI and GDI are objective measures derived from instrumented gait analysis [13–15]. A wide range of expense and expertise are required for these metrics, impacting clinical feasibility. The DGI requires only 20 feet of space, a flight of stairs, and a set of typically available clinical props [13]. The GVI requires instrumentation to acquire spatiotemporal parameters, whether it be an instrumented walkway, a set of inertial sensors, or a motion capture system [14]. The GDI involves the most expense and is the least clinically accessible, requiring 3D motion capture or other highly specialized technology and data analysis expertise [15]. However, with the advent of technologies like markerless motion capture and inertial measurement units (IMUs), indices that require kinematic measurement are becoming more clinically feasible with time [16–18]. We seek to develop an index that provides the quantitative insight and measurement accuracy found within the more computationally intensive indices, but to provide a tool that is eventually feasible for administration and interpretation in the clinic.

The objective of this study is to develop an Assessment of Bilateral Locomotor Efficacy (ABLE) that is a sensitive indicator of important biomechanical aspects of walking function in older adults and individuals with stroke-related gait dysfunction. We establish the ABLE in two phases. First, we develop the instrument via a thorough assessment of community-dwelling older adults. Second, we assess the ABLE in a retrospective analysis of a large sample of individuals post-stroke and community-dwelling adults.

2. Methods

Existing data from 14 community-dwelling older adults and 20 individuals post-stroke included kinematics and kinetics derived from 3D motion capture and spatiotemporal gait parameters obtained from overground walking [19]. The older adult data were used to develop the scoring scheme for the ABLE and are described as the development sample moving forward. The larger assessment sample was drawn from five previous studies conducted between 2007 and 2018 that used gait as an outcome variable. A subject was included in the assessment sample if they were not represented in the development dataset and all the necessary spatiotemporal and kinetic components were available. Additionally, all participants in the stroke group experienced a stroke at least six months prior to enrollment in the parent study. The initial pool consisted of 203 datasets, with 33 missing spatiotemporal or kinetic data and 18 participants that enrolled in more than one study. These criteria resulted in 85 individuals post-stroke and 33 community-dwelling older adults. Demographic data for the development and validation cohorts are available in Table 1.

Data collection occurred at the Rehabilitation Research and Development Center (VA Palo Alto Health Care System, Palo Alto, CA) or the Brain Rehabilitation Research Center (Malcom Randall VA Medical Center, Gainesville, FL). All procedures were approved by the Stanford University IRB or the University of Florida Health Science Center IRB, respectively. All participants gave written informed consent and all procedures were conducted in accordance with the Declaration of Helsinki.

Spatiotemporal characteristics of self-selected and fastest comfortable walking were assessed using a GAITRite pressure sensing walkway (Platinum Plus System, Version 3.89, Havertown, PA, USA). During self-selected walking trials, participants were instructed to walk at their comfortable pace. For the fastest comfortable walking trials, participants were instructed to walk as quickly and safely as they could as if they were crossing a busy intersection. Participants were given space to accelerate and decelerate beyond either end of the walkway. Data are reported as the average values from three passes across the walkway within each condition. Finally, 3D motion capture was used to assess kinematics and kinetics of self-selected walking. After review of all spatiotemporal measures in the 34-subject development cohort, critical biomechanical parameters known to contribute to gait function were selected as components that factored into total ABLE score (see results section for details). Although the intent was to build a metric based on spatiotemporal measures alone, the study team saw the need to review kinematic and kinetic measures of gait in order to differentiate among individuals with observable gait differences using as few of these measures as possible, with the future goal of finding surrogate metrics that require less instrumentation.

ABLE scores were assessed in the larger sample for concurrent validity by comparison to several assessments of lower extremity motor impairment and function, including: the motor subscale of the Fugl-Meyer Motor Assessment (FMA [20]); Berg Balance Scale (BBS [21]); Short Physical Performance Battery (SPPB [22]); and DGI [13]. Due to differing study protocols, not every clinical test was administered to every participant; sample sizes are noted within each comparison.

2.1. Data analysis

All statistical analyses were performed using R version 4.0.0 [23]. A

Table 1
Participant demographics. *Fugl-Meyer n = 63, 42 subjects are missing Fugl-Meyer motor scores. Data are presented as mean ± standard deviation, unless otherwise specified.

	Development		Validation	
	Control	*Stroke*	*Control*	*Stroke*
n	14	20	33	85
Age (years)	62 ± 9	65 ± 9	60 ± 10	61 ± 12
Sex (M/F)	8/6	17/3	16/17	66/19
Stroke Chronicity (years)	–	6.8 ± 5.1	–	3.8 ± 4.4
Fugl-Meyer Motor Score (median (range))	–	28 (12–34)	–	25 (8–33)*
Self-selected walking speed (m/s)	1.35 ± 0.18	0.81 ± 0.34	1.25 ± 0.23	0.56 ± 0.23

factor analysis was conducted on the full dataset (152 cases) to determine common factors or identify factors that did not fit well within the overall construct. We utilized the R psych package to conduct descriptive statistics, the Kaiser-Meyer-Olkin Measure of Sampling Adequacy, Bartlett's Test of Sphericity, and the overall factor analysis [24]. An oblique rotation (oblimin) was chosen due to investigator knowledge that the measured constructs are related, coupled with inspection of the correlation matrix. Results were inspected in the rotated and unrotated forms to ensure the rotation was adequate. Spearman's correlations were conducted to assess associations between ABLE scores and measures of lower extremity impairment and function. A Bonferroni correction was applied to the correlation analysis, resulting in $\alpha = 0.0125$.

3. Results

The ABLE consists of four components: self-selected walking speed (SSWS), speed change, non-paretic leg step length change, and peak concentric ankle plantarflexor power (A2) (Fig. 1). Each component is scored on a 0–3 scale, then all components are summed to achieve a total score, ranging from 0 to 12, where 12 indicates the highest level of function. Individual components are further detailed in the following paragraphs and component score cutoffs are shown in Table 2.

As previously detailed, walking speed is considered the sixth vital sign in adults and is frequently used to assess patients with motor impairment, so it was determined to be a necessary component in the ABLE [3]. SSWS was normalized to average leg length (i.e., average distance from greater trochanter to floor) with units of leg length per second [ll/s].

Ability to increase walking speed is essential for community mobility, such as crossing a busy street [3]. Speed change was calculated as the difference between fastest comfortable and self-selected walking speeds. Like SSWS, we expressed speed change in units of leg lengths per second [ll/s].

Table 2
Score cutoffs for each component value. Total score is calculated by summing the score from each component, with a maximum of 12 points. *Change in this context refers to the change from self-selected to fastest comfortable walking. ll: leg length, measured as average distance from greater trochanter to floor; A2: peak concentric ankle power.

	0	1	2	3
Self-selected Walking Speed [ll/s]	<0.3	0.3–0.75	0.75–1.0	>1.0
Speed Change* [ll/s]	<0.2	0.2–0.4	0.4–0.6	>0.6
Non-Paretic Leg Step Length Change [ll] *	<0.05	0.05–0.1	0.1–0.15	>0.15
A2 [W/kg]	<0.5	0.5–1.0	1.0–1.65	>1.65

Previous work indicates that higher functioning hemiparetic subjects and speed-matched healthy controls have significant differences in step length between self-selected and fast walking, while lower functioning hemiparetic subjects do not [25]. Non-paretic leg step length change (NP SL change) is the difference in step length between fastest comfortable and self-selected walking with reference to the non-paretic leg, expressed in leg lengths [ll]. In healthy older adults, we randomly assigned a test leg to use for calculating step length change and A2 (detailed below).

A2, the highest peak in the concentric ankle power profile, was selected because it is the primary joint power peak during gait, a biomechanical mechanism of forward progression, an indicator of capacity to scale and adjust walking speed in health, and has been found to differentiate high and low functioning hemiparetic individuals [25]. Ankle power is calculated using inverse dynamics as the product of joint moment and angular velocity. A2 was then normalized to body mass and expressed in units of watts per kilogram [W/kg]. Ankle power was

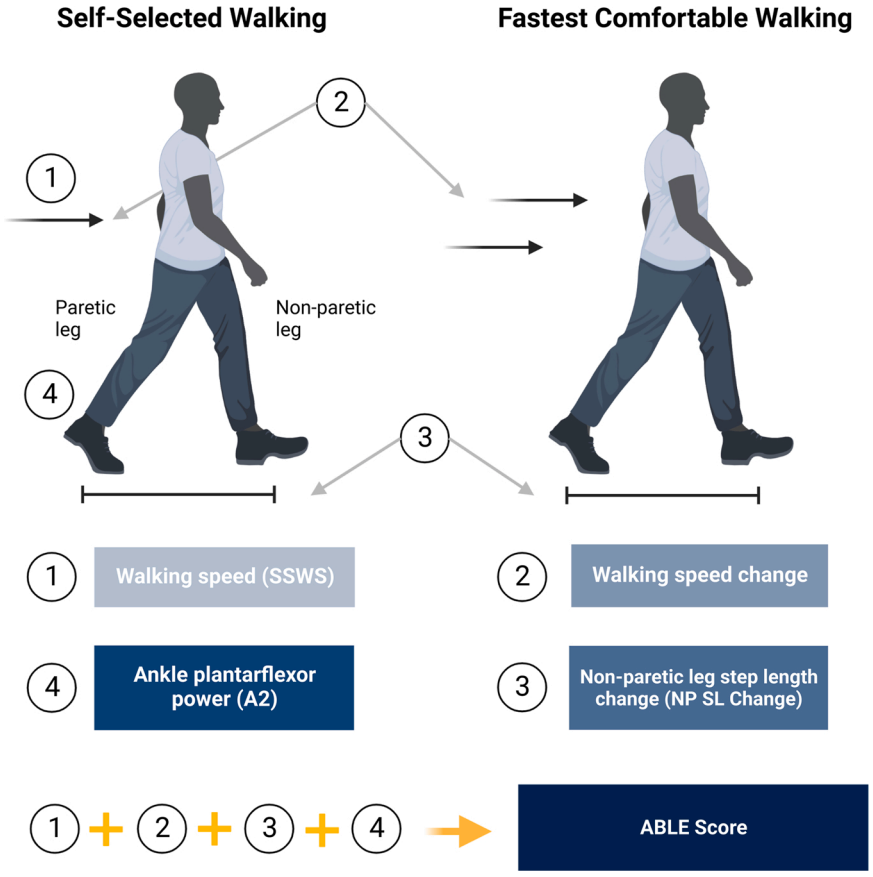

Fig. 1. The Assessment of Bilateral Locomotor Efficacy (ABLE) Index. Participants each walk at their self-selected (left) and fastest comfortable (right) walking speeds. Components of gait included in the ABLE are: 1) self-selected walking speed; 2) walking speed change from self-selected to fastest comfortable speed; 3) non-paretic leg step length change from self-selected to fastest comfortable speed; and 4) peak concentric ankle plantarflexor power (A2). Each component is scored on a 0–3 scale and the component scores are summed to produce an ABLE score. Created with BioRender.com.

measured on an instrumented split-belt treadmill for the instrument development sample, and either a split-belt treadmill (Bertec, Columbus, OH, USA, 200 Hz, n = 94) or three triaxial force plates (AMTI, Watertown, MA, USA and Bertec, Columbus, OH, USA, 100 Hz, n = 44) for the validation cohort. There were no differences in A2 measured between the treadmill and force plates ($p = 0.25$).

The development cohort had a median ABLE score of 10 with a range from 6 to 12.

3.1. Large cohort assessment

Community-dwelling older adults (median score 11, range 5–12) tended to score higher than individuals with chronic stroke (median 4, range 0–12) on the ABLE.

We conducted an exploratory factor analysis to determine the contributions of each component within the overall score. All four components are correlated, as evidenced by the correlation matrix in Table 3 and all p's < 0.001. The Kaiser-Meyer-Olkin measure of sampling adequacy for the overall analysis was 0.59, with all individual values exceeding the acceptable limit of 0.5 [26]. Bartlett's Test of Sphericity was significant ($p < 0.001$). Parallel Analysis indicated that two factors were sufficient to describe the dataset, with eigenvalues of 2.35 and 0.51 for the two factors, explaining 86 % of the variance in combination. Table 4 shows the factor loadings after rotation. The items that cluster on each factor suggest that factor 1 (SSWS and A2) may represent means of progression, while factor 2 (speed change and NP step length change) likely represents speed adaptability.

Total ABLE score was not significantly correlated with age across all individuals (Spearman's $\rho = -0.059$, $p = 0.47$) or within the stroke group ($\rho = 0.16$, $p = 0.11$), but there was a negative correlation between ABLE score and age in the control group ($\rho = -0.46$, $p < 0.01$). ABLE score was also not correlated with time post-stroke ($\rho = 0.024$, $p = 0.81$). Total ABLE scores positively correlated with all four standardized measures of motor impairment and function (all p's < 0.001). See Fig. 2 for correlations with clinical scores.

4. Discussion

The goal of this study was to develop an objective index of walking function in adults with stroke-related gait dysfunction and community-dwelling older adults. The ABLE consists of four important biomechanical components which are rooted in both theoretical frameworks and experimental evidence of walking function in older adults and individuals with hemiparesis. Factor analysis suggests this index has two major domains: one for progression and another for adaptability. Total ABLE scores are strongly associated with all the standardized clinical outcomes that were available within the larger dataset.

Theoretical frameworks, literature, and our analysis consistently suggest that forward progression and capacity to adapt are important aspects of human walking. Our factor representing forward progression aligns well with the theoretical frameworks of Gage and Perry [7,8]. Two other factor analysis studies resulted in factors related to forward progression. One included six spatiotemporal and kinematic variables in their analysis, with normalized gait speed being the only overlapping component between their metrics and the ABLE [27]. The other investigated 16 spatiotemporal parameters and concluded that gait speed, step length, and stride length represented a factor they labeled as 'pace' [28]. The second factor from our analysis points to the importance of adaptability within the walking environment. Humans must adapt their gait speed when walking in crowds or catching a bus, while other situations like hazards and uneven terrain may necessitate variation in step length [29]. While capacity to adapt may identify better candidates for rehabilitation, equally important is targeting improvement in this capacity as a rehabilitation goal. There are many ways a person can adapt their gait speed, through compensatory strategies or other means, not all of which are energetically appropriate [30].

When the ABLE was conceived to assess gait function following stroke, we anticipated that all included community-dwelling older adults would receive full marks across all categories, as they were recruited as healthy controls for each of their respective projects. Interestingly, 18 of the 47 total control participants scored a 9 or below, with approximately equal proportions of individuals from the development (5/14) and assessment (13/33) datasets. All these individuals met study inclusion criteria, had walking speeds within the normal range for their age, and lacked observable gait impairment to the trained research team. However, through obtaining a more extensive health history with the individuals within the development dataset, we learned that all five of these individuals had a significant medical concern that either did not meet our exclusion criteria or was undiagnosed at the time of recruitment and we were later informed of the diagnosis. These interesting findings suggest that further study is necessary to assess the utility of the ABLE to detect subclinical or emerging pathology in ostensibly healthy older adults.

Significant correlations between the ABLE and four clinical measures of impairment and function offer good concurrent validity with existing indices used in research or clinical practice. There is no gold standard with which to compare our index. The clinical measures compared here do not provide sufficient objectivity, suffer from ceiling effects, and most were not intended to measure the construct of gait. The factor analysis results suggest that the ABLE offers face validity, as it measures walking function along two domains. The relationship between age and ABLE score in healthy older adults is also a promising association, since walking function is known to decline with increasing age [31]. Future research should investigate both the test-retest reliability and inter-method reliability when using a variety of common tools to assess the components of the ABLE, such as video-based motion capture or with IMU-based measurement systems [16,17,32]. Additionally, the data analyzed for this project represent a convenience sample of participants that were mostly white and male. Future work needs to expand the diversity of validation data before the results can be generalized to the larger population.

The ABLE was developed to be straightforward and clinically accessible. For this reason, we attempted to avoid kinetic and kinematic variables requiring instrumented 3D motion capture. Techniques that measure abnormality in high-dimensional datasets like the GDI and the

Table 3
Correlation matrix of the four ABLE components. R values are reported. A2: peak concentric ankle power.

	Self-Selected Walking Speed	Speed Change	Non-Paretic Leg Step Length Change	A2
Self-Selected Walking Speed	1.00	0.59	0.28	0.79
Speed Change	0.59	1.00	0.84	0.57
Non-Paretic Leg Step Length Change	0.28	0.84	1.00	0.34
A2	0.79	0.57	0.34	1.00

Table 4
Summary of oblimin rotated factor loadings by score component. Factor loadings over 0.30 appear in bold. A2: peak concentric ankle power.

	Speed and Power	Adaptability
Self-Selected Walking Speed	**0.997**	—
Speed Change	0.26	**0.82**
Non-Paretic Leg Step Length Change	-0.12	**0.99**
A2	**0.76**	0.11

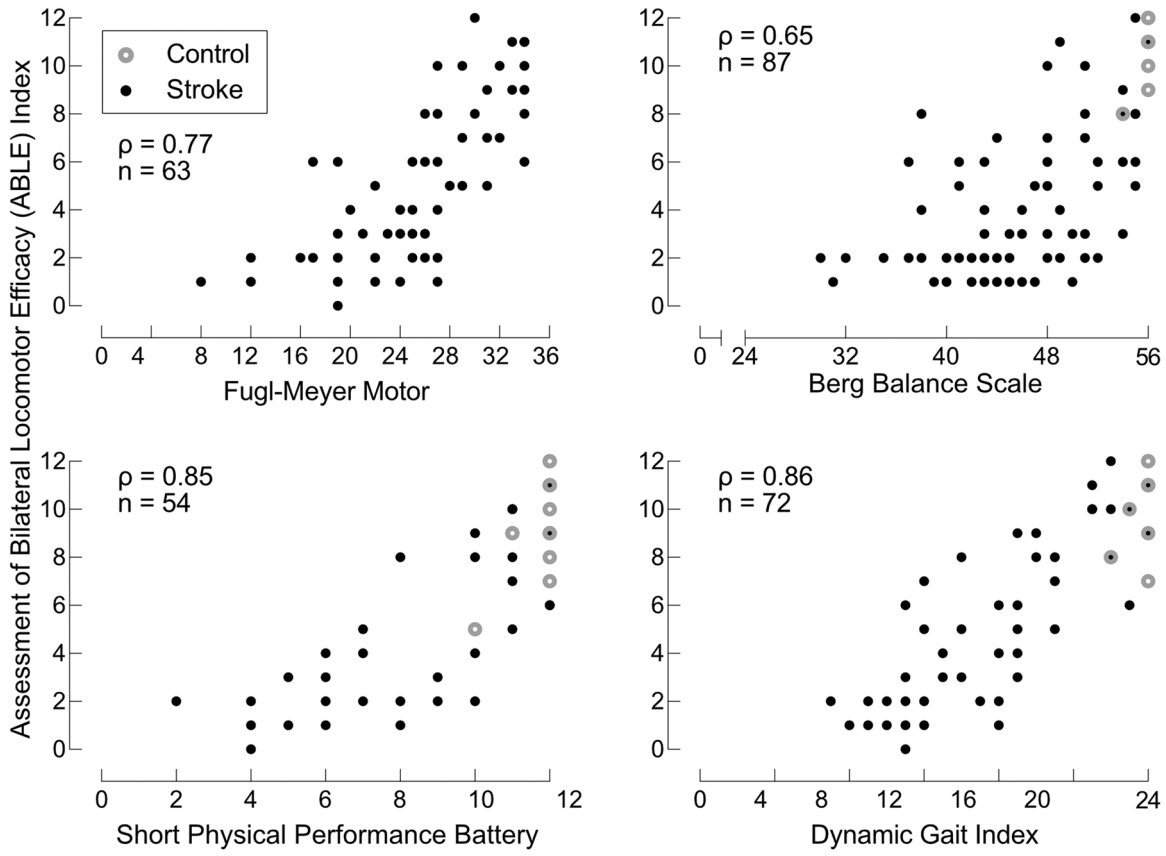

Fig. 2. Standard clinical metrics are positively correlated with ABLE Index. Scatterplots depict association between ABLE index score (y-axis) and clinical measures of impairment and function (x-axis), including Fugl-Meyer Motor Assessment (top left, stroke group only), Berg Balance Scale (top right), Short Physical Performance Battery (bottom left), and Dynamic Gait Index (bottom right). Open gray circles represent healthy individuals, while closed black circles represent individuals with chronic stroke. Spearman's Rho (ρ) and the number of participants included (n) are listed within each subplot.

abnormality R package created by Marks et al. follow this strategy, however they produce results that are difficult to interpret clinically [15,33]. We chose to use only a few outcomes, with a focus on spatiotemporal measures to make this index useable by a researcher or clinician without access to 3D motion capture. We made one exception in our current index – ankle power – which cannot be captured using spatiotemporal analysis alone and thus presents a limitation to the clinical accessibility of our index. However, plantarflexor power generation is a key indicator of gait function and a quantity known to decrease with aging and neurologic conditions such as stroke [25,31,34]. Further research needs to investigate whether there is a useable surrogate metric or a method to make measurement of joint powers more accessible. Spatiotemporal or kinematic measures like step length asymmetry and trailing limb angle are associated with paretic propulsion [35,36], but paretic propulsion still requires force measurement and the modest correlation with each of these surrogate metrics does not perform well enough to replace ankle power entirely. Emerging research indicates that ankle power or a surrogate metric may be estimated using IMUs [18,37]. These studies employed small samples of young, healthy adults and therefore require further testing in individuals with slower walking speeds and atypical gait patterns such as those seen in individuals post-stroke, but they do represent promising technological advances toward affordable and clinically accessible surrogates for A2.

This study provides evidence that this novel, four-component index is a valid indicator of walking function that appears to measure along two major factors. The ABLE addresses each of Gage's major prerequisites for normal walking: stance stability (SSWS, NP SL change), means of progression (A2), and energy conservation (speed change). With identification of a surrogate for ankle power and further assessment of reliability and predictive validity, the ABLE shows promise for use in both clinical and research settings for monitoring health status in older adults and rehabilitation efficacy of individuals with chronic stroke.

CRediT authorship contribution statement

Caitlin Banks: conceptualization, methodology, validation, formal analysis, data curation, writing – original draft, visualization. **Carolynn Patten:** conceptualization, methodology, resources, data curation, writing – review & editing, supervision, product administration, funding acquisition.

Declaration of Competing Interest

The authors, Drs. Caitlin L. Banks and Carolynn Patten, have no conflicts of interest to disclose.

Data availability

The data that support the findings of this study are available from the corresponding author, CP, upon reasonable request.

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