Gait & Posture 51 (2017) 91–96

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Residual standard deviation: Validation of a new measure of dual-task cost in below-knee prosthesis users

Charla L. Howard[a,b,*], Chris Wallace[a], James Abbas[c,1], Dobrivoje S. Stokic[b]

[a] Division of Orthotics and Prosthetics, Methodist Rehabilitation Center, Jackson, MS, United States
[b] Center for Neuroscience and Neurological Recovery, Methodist Rehabilitation Center, Jackson, MS, United States
[c] Center for Adaptive Neural Systems, Arizona State University, Tempe, AZ, United States

ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form 18 September 2016
Accepted 26 September 2016

Keywords:
Dual-task cost
Gait variability
Below knee prosthesis
Coefficient of variation
Stride length
Cadence

ABSTRACT

We developed and evaluated properties of a new measure of variability in stride length and cadence, termed residual standard deviation (RSD). To calculate RSD, stride length and cadence are regressed against velocity to derive the best fit line from which the variability (SD) of the distance between the actual and predicted data points is calculated. We examined construct, concurrent, and discriminative validity of RSD using dual-task paradigm in 14 below-knee prosthesis users and 13 age- and education-matched controls. Subjects walked first over an electronic walkway while performing separately a serial subtraction and backwards spelling task, and then at self-selected slow, normal, and fast speeds used to derive the best fit line for stride length and cadence against velocity. Construct validity was demonstrated by significantly greater increase in RSD during dual-task gait in prosthesis users than controls (group-by-condition interaction, stride length $p = 0.0006$, cadence $p = 0.009$). Concurrent validity was established against coefficient of variation (CV) by moderate-to-high correlations ($r = 0.50$–0.87) between dual-task cost RSD and dual-task cost CV for both stride length and cadence in prosthesis users and controls. Discriminative validity was documented by the ability of dual-task cost calculated from RSD to effectively differentiate prosthesis users from controls (area under the receiver operating characteristic curve, stride length 0.863, $p = 0.001$, cadence 0.808, $p = 0.007$), which was better than the ability of dual-task cost CV (0.692, 0.648, respectively, not significant). These results validate RSD as a new measure of variability in below-knee prosthesis users. Future studies should include larger cohorts and other populations to ascertain its generalizability.

1. Introduction

Effective control of gait requires complex coordination of multiple joints, limb segments, and muscles through various sensory-motor mechanisms. These control mechanisms modulate propulsion, braking, and body support during a gait cycle in response to ambulation goals and environmental demands. Despite the many complex mechanisms engaged, the resultant gait characteristics form consistent patterns of coordination. Most notably, stride length and cadence are modulated together forming a strong linear relationship along a broad range of gait speeds [1,2].

However, environmental influences and limitations inherent to human sensory-motor control introduce variability, which is apparent in healthy subjects and exaggerated after a neurological or musculoskeletal injury. For example, the strength of the linear relationship between stride length and cadence is weaker in Parkinson's disease [3] and prosthesis users [4] compared to unimpaired controls.

Disturbed sensory-motor control of gait in prosthesis users may be ascribed to a loss of limb, impaired sensation, or current limitations of prosthetic devices. This requires engaging additional motor and cognitive resources that impose load during performance of daily tasks. Not surprisingly, therefore, prosthesis users prefer componentry that they perceive less cognitively demanding [5–7]. The demand is amplified by frequent presence of cognitive impairments in prosthesis users [8].

Cognitive-motor interference is commonly induced with a dual-task paradigm, which requires performance of an additional task while walking. The increased load on the sensory-motor

* Corresponding author at: Methodist Rehabilitation Center, 1350 E. Woodrow Wilson Drive, Jackson, MS, 39216, United States.
E-mail address: choward@mmrcrehab.org (C.L. Howard).

[1] Dr. Abbas served as mentor to Charla Howard on her PhD dissertation at the Arizona State University, which includes research published herein that Mrs. Howard conducted with investigators from Methodist Rehabilitation Center.

http://dx.doi.org/10.1016/j.gaitpost.2016.09.025
0966-6362/

system typically alters gait and has been related to fall risk and instability [9–11]. Dual-task gait has more ecological validity than typical gait analysis and may elicit deviations not seen during regular walking [12,13]. Despite greater ecological validity and potential for improving sensitivity of gait studies, dual-task gait has not been extensively studied in prosthesis users. Some studies only looked at the cognitive performance [5,6], whereas others reported no significant increase in cognitive-motor interference in above-knee prosthesis users [14,15]. The reported absence of interference in the above-knee prosthesis users may be due to a small sample size, concurrent task selection, instructions about prioritization, substantial gait deviations in the single-task condition that constrained emergence of further perturbation under dual-tasking in order to preserve stability, or insensitive outcome measures.

The most commonly reported outcome in dual-task gait studies is the variability of temporal-spatial parameters [16,17]. The selected index of variability, however, is not uniformly defined or clearly justified with respect to studied gait parameters or experimental designs. Some studies use the standard deviation (SD) because it requires little data manipulation, thus, simplifying interpretation [17–19]. Most investigators report the coefficient of variation (CV), the ratio (%) of SD to the mean value of the parameter of interest. When examining variability, the relationship of gait parameters with velocity is typically not considered. However, because such relationships commonly exist, the parameter mean and SD are not independent of, or proportionally scaled with, velocity [18–20]. Thus, spontaneous or induced fluctuations in velocity may variably affect SD and mean values, leading to ambiguity in interpretation. This especially pertains to dual-task studies, because addition of a concurrent task tends to decrease velocity and alter related gait parameters [12,15,21]. Thus, there is a need to account for the impact of velocity on gait parameters for which the measures of variability are derived.

To control for velocity between conditions, previous studies have used a treadmill [22], analyzed data that fell within a narrow range of the prescribed speed [23], or made mathematical adjustments [24,25]. For example, Nordin et al. [25] used the linear relationship that step length and step time have with velocity to predict their values across a range of speeds and calculate the difference between the actual mean values and the predicted values for each condition. This reportedly improved detection of a dual-task cost (difference between single- and dual-task conditions). Because the mean values were used for calculating the dual-task cost, it was not possible to derive variability across multiple gait cycles. To overcome this, we extend the above approach by proposing a new method for analyzing variability in stride length and cadence that takes into account their close relationship with velocity. We termed this new index of variability the residual standard deviation (RSD), because it calculates a SD of the *vertical distance* between each actual data point and the point predicted by the best fit line between the velocity and stride length/cadence. Thus, RSD quantifies the variability of a departure from the linear relationship that stride length and cadence have with velocity across the range of self-selected walking speeds.

The purpose of this study was to validate the RSD method for calculating variability of stride length and cadence. For construct validity (aim 1), we compared changes in RSD from baseline to dual-task gait between below-knee prosthesis users and age/education-matched non-amputee controls. Aside from rare dual-task studies in this population, this choice was guided by our recent findings of the disrupted stride length-cadence relationship in below-knee prosthesis users [4]. The reduced automaticity (i.e., more variable sensory-motor output) was expected to be exaggerated during dual-task gait and captured by RSD. Concurrent validity (aim 2) was examined by correlating dual-task cost RSD with dual-task cost CV to infer to which degree the two measures probe the same construct. Discriminant validity (aim 3) was evaluated by examining the ability of dual-task cost RSD to differentiate below-knee prosthesis users from controls. As a follow-up, the discriminant ability of dual-task cost RSD was compared to the same ability of dual-task cost CV. Our first hypothesis was that RSD will capture larger variability in both stride length and cadence during dual-task gait in below-knee prosthesis users compared to controls. The second hypothesis was that dual-task cost RSD will positively and at least moderately correlate with dual-task cost CV. The third hypothesis was that the receiver operating characteristics (ROC) analysis based on dual-task cost RSD will yield a significant area under the curve (AUC) when comparing prosthesis users to controls.

2. Methods

2.1. Participants

A convenience sample of unilateral below-knee prosthesis users was recruited from clinics run by our institution. The inclusion criteria were ≥1 year since amputation; age 18–80 years; comfortable socket fit; no known balance, neurological, or other health problems that limit daily activities; and able to safely walk 10 m-distance at different velocities, as verified by a certified prosthetist. Age- and education-matched non-amputee subjects were recruited from the community to serve as controls. While not specifically matched for gender, we recruited more male subjects in the control sample to better approximate the prosthesis user population [26].

The sample included 13 controls (mean age 46 ± 18 years, 15 ± 2 years of education, BMI 26 ± 3, 8 men) and 14 below-knee prosthesis users (age 43 ± 12 years, 14 ± 2 years of education, BMI 26 ± 3, 11 men). The difference in the proportions of male vs. female subjects in the two samples was not significant (Fischer exact test, $p = 0.420$). The amputation occurred 9 ± 7 years (1.0–28) earlier due to trauma (n = 11), infection (n = 2), or vascular disease (n = 1). They were rated K3 (n = 13) or K4 (n = 1) on the Medicare scale and none used an assistive device. The study was approved by the institutional review board for human research and all subjects provided informed consent.

2.2. Protocol

Global cognitive function was evaluated using the Modified Mini-Mental Status Exam (3MS) and processing speed and executive function with Trail-Making forms (Trail) A and B while seated. Two cognitive tasks were selected for the dual-task paradigm; serial subtraction by 7 from a 3-digit number and backwards spelling of 5 letter words [27,28]. Each task was practiced twice before gait assessment.

For gait assessment, subjects walked over an electronic walkway (GAITRite®, length 5.2 m, width 0.6 m). An additional 1.2 m on each end allowed for acceleration/deceleration and recording of a steady state gait. Prior to data collection, subjects made six familiarization passes at normal self-selected speed. They were then instructed to walk at a comfortable pace and simultaneously perform the cognitive task without instructions on prioritization (dual-task gait). Each cognitive task was presented at random in a block of 6 passes. Walks were repeated if the subject stopped on the mat, walked off the side of the mat, had an erratic stepping pattern, or forgot the instructions. After the dual-task conditions, the subjects walked at self-selected normal, slow, and fast speeds, selected freely to ensure natural walking pattern (up to 6 passes each). The normal speed was always