Gait & Posture 41 (2015) 808–812

Contents lists available at ScienceDirect

Gait & Posture

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

Understanding dynamic stability from pelvis accelerometer data and the relationship to balance and mobility in transtibial amputees

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ARTICLE INFO

Article history:
Received 22 September 2014
Received in revised form 26 February 2015
Accepted 1 March 2015

Keywords:
Transtibial amputee
Dynamic stability
Acceleration
Wearable sensor
Gait

ABSTRACT

This study investigated whether pelvis acceleration-derived parameters can differentiate between dynamic stability states for transtibial amputees during level (LG) and uneven ground (UG) walking. Correlations between these parameters and clinical balance and mobility measures were also investigated. A convenience sample of eleven individuals with unilateral transtibial amputation walked on LG and simulated UG while pelvis acceleration data were collected at 100 Hz. Descriptive statistics, Fast Fourier Transform, ratio of even to odd harmonics, and maximum Lyapunov exponent measures were derived from acceleration data. Of the 26 pelvis acceleration measures, seven had a significant difference ($p \leq 0.05$) between LG and UG walking conditions. Seven distinct, stability-relevant measures appeared in at least one of the six regression models that correlated accelerometer-derived measures to Berg Balance Scale (BBS), Community Balance and Mobility Scale (CBMS), and Prosthesis Evaluation Questionnaire (PEQ) scores, explaining up to 100% of the variability in these measures. Of these seven measures, medial–lateral acceleration range was the most frequent model variable, appearing in four models. Anterior–posterior acceleration standard deviation and stride time appeared in three models. Pelvis acceleration-derived parameters were able to differentiate between LG and UG walking for transtibial amputees. UG walking provided the most relevant data for balance and mobility assessment. These results could translate to point of patient contact assessments using a wearable system such as a smartbelt or accelerometer-equipped smartphone.

1. Introduction

Movement stability is essential for safe and secure walking whether on level ground or more challenging terrain. Compromised dynamic stability can adversely affect gait confidence and activities of daily living [1]. The dynamic stability of people with lower extremity amputations is especially challenged by internal factors, such as minimal somatosensory prosthetic limb information and reduced musculature to generate necessary stabilizing forces [2], increasing fall risk compared to able-bodied peers [3,4]. Environmental factors, such as variable terrain or an unstable surface, further challenge dynamic stability by introducing unpredictable changes in limb support [5]. A better understanding of the kinematics associated with amputee accommodations to maintain dynamic stability would aid healthcare providers in making evidence-based decisions for prosthesis configuration, therapy, and gait training. Quantitative measures of amputee dynamic movement stability provided by an easy-to-wear device that can be applied at the point-of-care, such as an accelerometer, would be ideal.

Accelerometers are appropriate for point-of-care assessments due to their low weight and cost. These sensors are extensively used to assess stability and fall risk in older individuals [6], but less work has been done using accelerometers to assess amputee gait stability. Four studies [7–10] used accelerometers to identify differences between lower limb amputees and able-bodied individuals. Bussmann et al. [7] determined that acceleration-derived body motility was less in lower limb amputees than able-bodied individuals, possibly due to the slower amputee walking speed.

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http://dx.doi.org/10.1016/j.gaitpost.2015.03.001
0966-6362/

Lamoth et al. [8] determined that lower back acceleration-derived local stability exponent and sample entropy were significantly greater for transfemoral amputees (TFA) than able-bodied individuals, indicating that TFA acceleration patterns are less regular and locally stable. Tura et al. [9] determined that acceleration-derived unbiased autocorrelation coefficient peaks from acceleration at the xiphoid process were lower in TFA than able-bodied individuals, indicating reduced symmetry and regularity in amputee gait. Using lower-back mounted accelerometers, Iosa et al. [10] found less stability, measured as the root mean square of several acceleration parameters, in TFA and transtibial amputees (TTA) compared to able-bodied individuals. These studies indicated that accelerometers can identify differences between lower-limb-amputee and able-bodied gait. Iosa et al. [10] also found lower TFA stability with locked-knee prostheses compared to TFA with unlocked knee prostheses and TTA (vertical axis only). Parker et al. [11] used accelerometers to identify differences between TTA fallers and non-fallers, and determined that vertical step regularity, derived from an unbiased autocorrelation analysis of trunk acceleration, was significantly related to fall history. It achieved poor to fair discriminability between fallers and non-fallers [11]. Therefore, there is a need to identify acceleration-derived parameters that can better differentiate between TTA dynamic stability states. It may be possible to leverage acceleration-derived variables that have successfully distinguished between stability and fall risk levels in a different population with stability problems, such as older individuals [6]. It is also important to determine how stability parameters relate to clinical outcome measures commonly used in amputee rehabilitation.

The purpose of this study was to investigate if pelvis-mounted-accelerometer derived measures can differentiate between dynamic stability states for different TTA walking activities and determine how these measures relate to common clinical outcome measures in amputee rehabilitation. A pelvis-mounted accelerometer was employed to enable wearable accelerometer use at the point-of-care. These accelerometer measures may identify instability inducing gait deficiencies and gait accommodations employed by amputees to maintain stable gait. A model of the relationship between acceleration-based-measures and clinical outcome measures can be used when selecting the best acceleration-based-measures for clinical decision-making. Wearable-sensor-based models that correlate well with clinical outcome measures could provide immediate information on functional-status when performing a variety of movement activities.

2. Methods

2.1. Participants

A convenience sample of 11 individuals with unilateral transtibial amputation, who were independent community ambulators (K-level 3 or 4) [12], voluntarily participated in this study. The participants had an average age of 61.78 ± 16.11 years (range: 40–90 years), weight of 85.77 ± 14.40 kg (range: 52–105 kg), and 23.95 ± 24.74 years (range: 1–66 years) of prosthetic experience. All participants were screened by a physiatrist and prosthetist to ensure safe participation and all participants gave informed written consent. The Ottawa Health Sciences Network Research Ethics Board approved this study.

2.2. Protocol

Participants first completed the Community Balance and Mobility Scale (CBMS) and Berg Balance Scale (BBS), which are measures of balance and mobility [13,14]. The CBMS [13] and BBS [14] are the total of individual item scores ranging from 0 (worst) to 5 (best) with a maximum total score of 96, and 0 (worst) to 4 (best) with a maximum total score of 64, respectively.

An Xsens accelerometer (30 g) was secured to the participant's posterior pelvis, over the sacrum, with double-sided tape adhered directly to the skin to minimize movement artifacts and the Xbus wireless unit (268 g) was secured to a belt worn at the waist. Accelerometer data were collected at 100 Hz for two walking scenarios: level ground (LG) walking on a 10 m walkway and simulated uneven ground (UG) walking on an 8 m walkway covered in foam mats. Five trials were recorded for each scenario, with scenario order randomized for each participant. A person walked beside each participant throughout the walking trials for safety.

Finally, the participant completed the Prosthesis Evaluation Questionnaire (PEQ), a self-report questionnaire for prosthesis function, mobility, psychosocial state, and well-being [15], where the PEQAmb (ambulation sub-score) was the average of eight ambulation question scores ranging from 0 (worst) to 100 (best).

2.3. Data processing

Accelerometer data were exported to Matlab v2010a to calculate outcome variables. The positive vertical axis was in the upward direction, positive anterior–posterior (AP) axis was in the anterior direction, and positive medial–lateral (ML) was toward the participant's right side. Individual strides were identified from foot contact times. Foot contact time was identified by trough detection in the vertical acceleration data, since vertical acceleration reached a local minimum just before heel contact followed by a rapid upward acceleration [16]. Trough detection was performed using Matlab R2010a and was manually confirmed through visual inspection of plotted vertical acceleration data. Accelerometer-derived measures were:

- Descriptive statistics: Minimum, maximum, range, mean, and standard deviation of acceleration for the vertical, AP, and ML axes.
- Temporal: Stride time was calculated as the time between same foot contacts. Cadence was calculated as the reciprocal of the time between consecutive foot contacts.
- Fast Fourier Transform (FFT) First Quartile: Percentage of motion frequencies in the first quartile of an FFT frequency plot for vertical, AP, and ML acceleration.
- Ratio of even to odd harmonics: Proportion of the acceleration signal that is in phase with the participant's stride frequency. The harmonic ratio was calculated for the vertical, AP, and ML axes using the technique presented in [17].
- Maximum Lyapunov exponent: This local dynamic stability measure is the average rate of expansion or contraction of the original trajectory in response to perturbations [18,19]. The maximum Lyapunov exponents for vertical, AP, and ML acceleration were calculated as in [20] with the number of dimensions determined using the global false nearest neighbors method [21] and a fixed time delay based on the first minimum of the average mutual information [22].

Acceleration data were filtered using a fifth order, low pass Butterworth filter with a cut-off frequency of 12.5 Hz for descriptive statistics and maximum Lyapunov exponent parameters. Unfiltered acceleration data were used to calculate the FFT first quartile and the ratio of even to odd harmonics to ensure that all frequency information remained intact.

2.4. Data analysis

For each participant, walking variables for LG and UG were averaged over all strides and trials. Paired statistical tests (SPSS