Clinical Biomechanics 32 (2016) 241–248

Contents lists available at ScienceDirect

Clinical Biomechanics

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

Understanding responses to gait instability from plantar pressure measurement and the relationship to balance and mobility in lower-limb amputees

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ARTICLE INFO

Article history:
Received 17 December 2014
Accepted 16 November 2015

Keywords:
Transfemoral amputee
Transtibial amputee
Center of pressure
Plantar pressure
Stability
Gait

ABSTRACT

Background: Measuring responses to a more unstable walking environment at the point-of-care may reveal clinically relevant strategies, particularly for rehabilitation. This study determined if temporal measures, center of pressure-derived measures, and force impulse measures can quantify responses to surface instability and correlate with clinical balance and mobility measures.
Methods: Thirty-one unilateral amputees, 11 transfemoral and 20 transtibial, walked on level and soft ground while wearing pressure-sensing insoles. Foot-strike and foot-off center of pressure, center of pressure path, temporal, and force impulse variables were derived from F-Scan pressure-sensing insoles.
Findings: Significant differences ($P < 0.05$) between level and soft ground were found for temporal and center of pressure path measures. Twenty regression models ($R^2 \le 0.840$), which related plantar-pressure-derived measures with clinical scores, consisted of nine variables. Stride time was in eight models; posterior deviations per stride in six models; mean CoP path velocity in five models; and anterior–posterior center of pressure path coefficient of variation, percent double-support time, and percent stance in four models.
Interpretation: Center of pressure-derived parameters, particularly temporal and center of pressure path measures, can differentiate between level and soft ground walking for transfemoral and transtibial amputees. Center of pressure-derived parameters correlated with clinical measures of mobility and balance, explaining up to 84.0% of the variability. The number of posterior deviations per stride, mean CoP path velocity stride time, anterior–posterior center of pressure path coefficient of variation, percent double-support time, and percent stance were frequently related to clinical balance and mobility measures.

1. Introduction

Movement stability is critically important for people with lower extremity amputations (Svoboda et al., 2012) since they have a greater risk of falling compared to their able-bodied peers (Miller et al., 2001). Movement stability also affects gait confidence and ultimately activities of daily living, work, and leisure (Kulkarni et al., 1996). Dynamic stability is challenged by internal factors, such as reduced force generation and minimal somatosensory information by the prosthetic limb (Hermodsson et al., 1994) that alter lower-limb mechanics (Vanicek et al., 2009). Environmental factors, such as soft or uneven terrain, cause small, unpredictable changes in limb support that challenge dynamic stability and increase fall risk (Curtze et al., 2011). Soft or compliant terrain reduces kinesthetic perceptions of body orientation with respect to the ground and can induce mechanical perturbations due to compression of the compliant surface (MacLellan and Patla, 2006).The ability to measure the subsequent gait responses to surface-related instability at the point-of-care may be useful in revealing clinically relevant strategies used by amputees to overcome instability due to internal or environmental factors. This knowledge may lead to improved interventions for prosthesis users.

For transfemoral amputees (TFA), assessments that could be used at the point-of-care have focused predominantly on body-worn accelerometers. Body-worn accelerometers and gyroscopes have been used to identify less stable gait patterns (Lamoth et al., 2010) and reduced gait symmetry and regularity (Tura et al., 2010) in TFAs compared to able-bodied individuals. Accelerometers have also been used to detect gait differences between TFAs, transtibial amputees (TTAs), and able-bodied individuals, suggesting that accelerometer-

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http://dx.doi.org/10.1016/j.clinbiomech.2015.11.004

derived gait measures can be sensitive to degree of impairment (Iosa et al., 2014). While inertial sensors have identified gait stability differences between amputees and able-bodied individuals, these sensors only provide data about specific body segment movement through space. Complementary information from sensors at the foot-shoe interface could further our understanding of TFA stability-related gait changes.

Amputee gait stability changes for TTAs have been investigated using wearable sensors (Kendell et al., 2010) or lab-based motion capture and force plate technology (Vanicek et al., 2009; Curtze et al., 2011). Kendell et al. (2010) used wearable pressure-sensing insoles to detect stability parameter asymmetry between the intact and prosthetic limbs in TTA gait. Gait adjustments to different walking environments (i.e. uneven ground, ramps, stairs) were more apparent for the intact limb, which had a greater ability to control for instability compared to the prosthetic limb (Kendell et al., 2010). TTA participants also adopted a more cautious gait pattern on level ground compared to their able-bodied peers by minimizing anteroposterior (AP) and mediolateral (ML) center of pressure (CoP) deviations (Kendell et al., 2010). These results showed the potential of wearable sensor-derived plantar pressure gait data to detect stability-related gait changes.

Six parameters, derived from CoP and temporal data acquired using wearable plantar pressure insoles and data acquisition hardware, have been identified as viable dynamic stability measures (Biswas et al., 2008; Kendell et al., 2010). These parameters were direction changes in AP and ML CoP, repeated loading in local foot regions, maximum lateral force placement, stride time, and double-support time (DST). While these outcome measures were useful in understanding dynamic stability in amputee gait, clinical validity was not assessed. Other biomechanical measures could also be considered as indicators of gait adaptation to instability; such as CoP velocity, impulse, and foot-ground contact position. The clinical validity of these biomechanical measures can be assessed by testing for a relationship with common clinical assessment tests; such as, Berg Balance Scale (BBS, Berg et al., 1989), Community Balance and Mobility Scale (CBMS, Howe et al., 2006), and Prosthesis Evaluation Questionnaire (PEQ, Legro et al., 1998). Clinical decision-making at the point-of-care, such as identifying amputees with stability issues, could be improved with quantitative, objective biomechanical measures that demonstrate clinical validity. These models and biomechanical measures may identify potential gait issues, exacerbated by unstable walking environments, that warrant further investigation to identify underlying deficiencies.

The current study builds on the earlier investigation by Kendell et al. (2010), by using a larger, more detailed set of variables to determine if additional temporal, modified, and additional CoP-derived measures and new force impulse measures are suitable to identify and quantify gait changes that occur when TFAs and TTAs are challenged with an unstable walking environment. Models were developed from these measures and BBS, CBMS, and PEQ to show relationships that bridge between biomechanical and clinical measures of balance and mobility. Wearable-insole-sensor-based models that correlate well with clinical outcome measures could provide immediate, quantitative information on amputee gait changes in response to surface instability and potential gait issues, which may require further, focused investigation to indentify underlying deficiencies.

2. Methods

2.1. Participants

Thirty-one individuals with unilateral amputations, who were independent community ambulators (K-level 3 or 4) (HCPCS, 2001) and had at least 1 year of prosthetic experience, voluntarily participated in this study. Eleven participants were TFA with an average age of 54.88 (14.98) years, weight of 73.83 (11.58) kg, and 36.80 (20.17) years of prosthetic experience. Seven TFAs used an Otto Bock C-Leg, and four used other hydraulic knees with no microprocessor control. Twenty participants were TTA with an average age of 61.06 (14.11) years, weight of 79.25 (16.10) kg, and 21.21 (21.64) years of prosthetic experience. The cause of amputation was trauma (n = 20), peripheral vascular disease (n = 6), tumor (n = 3), diabetes (n = 1), and frostbite (n = 1). All participants were screened by a physiatrist and prosthetist to ensure safe participation. The Ottawa Health Sciences Network Research Ethics Board approved this study and all participants gave informed written consent.

2.2. Clinical assessments

BBS measures balance impairment by assessing functional task performance using tasks such as sitting, standing, transfers, turning, object retrieval, and reaching (Berg et al., 1989). BBS has demonstrated validity and reliability as a measure of balance in lower-limb amputees (Major et al., 2013; Wong et al., 2013); however, Wong et al. (2013) indicated a ceiling effect. Therefore, CBMS, although not yet validated in a lower-limb amputee population, was also included since it is less sensitive to ceiling effects, when used to assess ambulatory individuals with traumatic brain injuries (Inness et al., 2011). CBMS measures balance and mobility by assessing performance for 13 activities including standing, various walking tasks, running, turns, hopping, dodging, and stairs (Howe et al., 2006). PEQ is a self-report questionnaire for prosthesis function, mobility, psychosocial state, and well-being that has good validity and reliability with lower-limb amputees (Legro et al., 1998).

2.3. Protocol

Participants completed the BBS and CBMS before completing the walking tests. F-Scan pressure-sensor insoles (Tekscan, Inc., 307 West First Street, South Boston, MA, USA) were trimmed and fit into each participant's everyday footwear on top of the shoe insole. F-Scan insoles are a thin (0.18 mm) printed circuit insole with 960 individual sensors and a sensor density of 3.9 sensors/cm^2. Plantar pressure data were collected at 120 Hz using the F-Scan Mobile system during two walking scenarios: level ground (LG) walking on a 10 m walkway and soft ground (SG) walking on an 8 m walkway covered in standard, medium density foam fitness mats to create an unstable walking environment. 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. After completing the walking trials, the participant completed the PEQ.

2.4. Data processing

Plantar pressure data were exported to Matlab v2010a (Mathworks, Inc., 3 Apple Hill Drive, Natick, MA, USA) to calculate outcome variables. CoP was calculated using Eqs. 1 and 2:

$$X_{CoP} = \frac{\sum_{i=0}^{m-1}\left(i\sum_{j=0}^{n-1} F_{ij}\right)}{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} F_{ij}} \quad (1)$$

$$Y_{CoP} = \frac{\sum_{i=0}^{m-1}\left(i\sum_{j=0}^{n-1} F_{ij}\right)}{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} F_{ij}} \quad (2)$$

where F_{ij} is the force at sensel column i, and sensel row j, m is the number of sensel columns, n is the number of sensel rows, X_{CoP} is the AP CoP sensel location, and Y_{CoP} is the ML CoP sensel location (Tekscan, 2007).