Gait & Posture 38 (2013) 858–863

Contents lists available at SciVerse ScienceDirect

Gait & Posture

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

The effects of walking speed and prosthetic ankle adapters on upper extremity dynamics and stability-related parameters in bilateral transtibial amputee gait

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ARTICLE INFO

Article history:
Received 25 September 2012
Received in revised form 2 April 2013
Accepted 17 April 2013

Keywords:
Bilateral
Transtibial amputation
Gait
Center-of-mass
Trunk

ABSTRACT

Bilateral transtibial amputee (BTA) gait has been investigated less and is not as well understood compared to that of their unilateral counterparts. Relative to able-bodied individuals, BTAs walk with reduced self-selected speeds, increased step width, hip-hiking, and greater metabolic cost. The clinically observed upper body motions of these individuals have not been quantified, but appear substantially different from able-bodied ambulators and may impact upright balance. Therefore, the objective of this study was to characterize the upper extremity kinematics of BTAs during steady-state walking. We measured medial-lateral ground reaction forces, step width and extrapolated center-of-mass (XCoM) trajectory, and observed effects of walking speed and increased prosthetic ankle range-of-motion (ROM) on these parameters. Significantly, BTAs display greater lateral trunk flexion ROM and shoulder abduction than able-bodied individuals when walking at similar speeds, and the inclusion of prosthetic adaptors for increasing passive ankle ROM slightly reduced step width. Overall, exaggerated lateral trunk flexion ROM was invariant with step width. Results suggest that lateral trunk motion is useful for shifting the body center-of-mass laterally onto the leading stance limb while simultaneously unloading the trailing limb. However, exaggerated lateral trunk flexion may introduce an unstable scenario if the XCoM is displaced beyond the lateral base-of-support. Further studies would be useful to identify if either prostheses that assist limb advancement and/or gait training may be effective in reducing this lateral sway while still maintaining efficient ambulation.

1. Introduction

Compared to unilateral transtibial amputees, bilateral transtibial amputee (BTA) gait has received relatively less attention and this has limited our understanding of the unique rehabilitation needs of these individuals [1]. Recent investigations have demonstrated that BTAs walk with substantially reduced self-selected speeds and increased step width compared to able-bodied individuals [2]. Furthermore, despite close to normal knee and hip joint kinematics during the swing phase of gait, these individuals display considerable hip-hiking [2]. These compensatory gait mechanisms may contribute to their increased metabolic cost, which is reportedly 1.3–2.2 times higher than able-bodied individuals [3–5]. Importantly, exaggerated upper body motions, such as lateral trunk sway and abducted arms, have been observed clinically. In order to inform prosthetic prescription guidelines and other rehabilitation interventions for ensuring safe and efficient mobility of these individuals, it is important to understand the role these upper body motions play during gait and their relationship with upright balance.

Upright balance during gait is of significant concern as lower limb amputees are at an increased fall risk, and hence fall-related injuries, compared to able-bodied individuals. Indeed, 52.4% of community-dwelling unilateral lower limb amputees reported at least one fall within the past year [6] and have reduced balance confidence [7]. This increased fall risk is a function of reduced capability to produce rapid compensatory movements to maintain the body center-of-mass (BCoM) within the base-of-support (BoS) [8,9], resulting from diminished sensory feedback [10–13], reduced muscle strength [14,15], and inability to actively adjust the mechanical behavior of the prosthesis (i.e., joint movement and impedance) [9,16–20]. BTAs are at a further disadvantage as they lack additional compensatory mechanisms otherwise provided by the sound limb.

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0966-6362/$ – see front matter
http://dx.doi.org/10.1016/j.gaitpost.2013.04.012

Anecdotally, it appears that the motions of the arms and trunk during BTA gait may play a substantial role in ambulation and upright balance. However, their upper body dynamics have not yet been characterized, thereby limiting understanding of their function and effects on gait. Therefore, the primary objective of this retrospective study was to quantify the upper body kinematics of BTAs during steady-state walking. A secondary objective was to observe the effects of walking speed and prosthetic ankle adaptors that allow for increased ROM on these characteristics to provide insight into gait adaptations and prescription guidelines. Further insight into these dynamics may help inform intervention strategies to satisfy the unique ambulatory and rehabilitation needs of these individuals with the objective of maximizing upright balance.

2. Methods

2.1. Subjects

A retrospective analysis was performed on ten BTA subjects (50 ± 18 years, 1.73 ± 0.08 m, 82 ± 16 kg) from a previous investigation (ethical approval and informed consent previously obtained) [2,21,22]. Subject inclusion criteria required that they: walk freely without the use of an aid; be a minimum of two years post-amputation; have independent functional ambulation; and possess no other pathological conditions that might affect ambulation or balance. Amputation etiology included: vascular ($n = 5$), traumatic ($n = 3$), congenital ($n = 1$), and meningitis ($n = 1$). Data for 13 age- and speed-matched able-bodied controls (51 ± 6 years, 1.72 ± 0.09 m, 74 ± 15 kg) were used for comparison.

2.2. Experimental protocol

Subjects performed overground walking trials along a ten meter level walkway at three self-selected speeds in this order: (1) "normal," (2) "fastest comfortable" (fast), and (3) "slowest comfortable" (slow). Data were collected while subjects walked with two prosthetic configurations (same configuration for each leg) that are representative of different levels of prosthetic ankle joint motion: (PC1) Seattle Lightfoot II prosthetic foot (Seattle Systems, Poulsbo, WA), and (PC2) Seattle Lightfoot II foot, Multiflex Ankle (Endolite, Miamisburg, OH), and Torsion Adapter (Ottobock, Duderstadt, Germany). The combined adapters of PC2 provide additional motion in the sagittal, frontal, and transverse planes and were thus used to observe prosthetic effects on all planes of kinematic movement. Components were individually prescribed based on subject height, weight, and activity level, and were attached to the subjects' own socket and suspension for testing. Prostheses were aligned by the same certified prosthetist, PC1 was always tested before PC2, and subjects were permitted two weeks for acclimation prior to data collection.

2.3. Data collection and analysis

Kinematic data were collected with a digital motion capture system (Motion Analysis Corporation (MAC), Santa Rosa, CA) at 120 Hz using a lower extremity Helen Hayes marker set [23] with additional markers on the right and left acromion process and lateral epicondyle of the humerus. Kinetic data were collected at 960 Hz with six force plates (AMTI, Watertown, MA) embedded within the walkway. Upper body kinematics (i.e., shoulder abduction and trunk lateral flexion, transverse rotation, and forward flexion), ankle kinematics (i.e., plantar/dorsiflexion and transverse rotation), step width, medial-lateral ground reaction force (MLGRF), and speed were determined across five walking trials for each walking and prosthetic condition using OrthoTrak software (MAC). The trunk reference frame was defined by the two acromion markers and pelvis reference frame center: medial–lateral axis—line connecting acromion markers; inferior–superior axis—line connecting midpoint between acromion markers and pelvis reference frame center; anterior–posterior axis—orthogonal to the plane formed by the other two axis. All trunk angles are estimated relative to the laboratory reference frame (i.e., zero angular displacement represented by coincidence of the trunk reference frame with the laboratory reference frame). Shoulder abduction was defined as the relative angle between the inferior–superior axis of the trunk and upper arm segment defined by the acromion and epicondyle marker. Kinematic and kinetic data were filtered with a bidirectional 4th order low-pass Butterworth filter at 6 and 10 Hz, respectively. Right–left gait symmetry was established for these subjects in a previous investigation [21] and data were averaged across both legs for each subject over a minimum of ten steps for all conditions. Kinetic data were normalized by subject body weight (BW).

BCoM position for each subject was estimated in OrthoTrak from the anthropometric segmental mass properties of able-bodied individuals. The XCoM—an estimated vertical projection of the BCoM plus its velocity component as normalized by the leg eigenfrequency [8,9]—was calculated using custom software in Matlab (Mathworks, Natick, MA). The XCoM can be used to provide an estimation of the *lateral margin of stability*, which is the instantaneous distance between the position of the XCoM and approximated center-of-pressure (CoP) under the stance limb representative as the lateral BoS. A negative margin of stability (i.e., XCoM beyond the lateral edge of the BoS) indicates a dynamically unstable scenario when action must be taken by the ambulator to redirect the XCoM and avoid a fall [8,9].

Because the BTA subjects walked slower than the able-bodied controls at the slow and normal speeds, only data from the BTA subjects' fast walking trials can be used for speed-matched comparisons with able-bodied data.

2.4. Statistical analysis

Kinematic data were averaged over all ten BTA subjects, while kinetic data were averaged over nine subjects due to a hardware malfunction. A two-way repeated-measures ANOVA was used to statistically analyze between-speed differences of amputee parameters, effects of prosthetic configuration, and interactions between speed and prosthetic configuration. A Bonferroni adjustment was used for multiple comparisons during posthoc analyses. An independent *t*-test was used to compare amputee and able-bodied data. Relationship between two variables was assessed by the Pearson's Correlation. Data normality and sphericity were confirmed using the Shapiro–Wilk and Mauchly's test, respectively. If the sphericity assumption was violated, a Greenhouse–Geisser correction was used and the results interpreted accordingly. Statistical analyses were conducted using SPSS (IBM, Armonk, NY) and the critical alpha was set at 0.05.

3. Results

BTA subjects displayed an average increase in prosthetic ankle motion of $2 \pm 3^\circ$, $2 \pm 4^\circ$, and $3 \pm 4^\circ$ in transverse ROM ($p = 0.096$), and $5 \pm 3^\circ$, $6 \pm 3^\circ$, and $5 \pm 3^\circ$ in sagittal (i.e., plantar/dorsiflexion) ROM ($p < 0.001$) with the use of PC2 during slow, normal, and fast walking, respectively.

Peak shoulder abduction angles of the amputee subjects were greater than able-bodied controls ($p < 0.001$ at similar walking speed; Fig. 1), and were directly proportional with speed ($p = 0.001$). Amputees displayed a sinusoidal profile of lateral trunk flexion (Fig. 2A) with a ROM that was substantially greater