Clinical Biomechanics 30 (2015) 1225–1229

Contents lists available at ScienceDirect

Clinical Biomechanics

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

Step activity and stride-to-stride fluctuations are negatively correlated in individuals with transtibial amputation

Jenny A. Kent [a], Nicholas Stergiou [a,b], Shane R. Wurdeman [a,c,*]

[a] Biomechanics Research Building, University of Nebraska at Omaha, 6160 University Drive, Omaha, NE 68182-0860, USA
[b] College of Public Health, 984355 University of Nebraska Medical Center, Omaha, NE 68198-4355, USA
[c] Hanger Clinics dba Advanced Prosthetics Center, 9109 Blondo St, Omaha, NE 68134, USA

ARTICLE INFO

Article history:
Received 24 May 2015
Accepted 31 July 2015

Keywords:
Biomechanics
Human movement variability
Amputee
Rehabilitation
Lyapunov exponent

ABSTRACT

Background: Variability occurs naturally from stride to stride in healthy gait. It has been shown that individuals with lower limb loss have significantly increased stride-to-stride fluctuations during walking. This is considered indicative of movement disorganization and is associated with less healthy movement. Given that lower limb prosthesis users perform on average less physical activity than able bodied individuals, the purpose of this study was to determine whether increased fluctuations also correspond to a reduced level of activity in daily life.

Methods: Twenty-two transtibial amputees wore an activity monitor (Actigraph, Pensacola, FL, USA) for 3 weeks. Lower limb kinematics during treadmill walking were measured using a 12-camera motion capture system. The largest Lyapunov exponent (λ) was calculated bilaterally at the ankle, knee and hip to quantify the stride-to-stride fluctuations of the lower limb joints. Pearson correlations were used to identify the relationships between the average daily step count over the 3 week collection period and λ.

Findings: Significant, moderate negative correlations between daily step count and λ were found at the intact ankle ($r = 0.57$, $P = 0.005$), and the knee on the affected side ($r = 0.44$, $P = 0.038$). No such correlation was found at any other lower limb joint.

Interpretation: The negative correlation evident at these two joints demonstrates that increased stride-to-stride fluctuations are related to decreased activity levels, however it remains unclear whether these changes in the stride-to-stride fluctuations promote decreased activity or whether less active individuals do not gain sufficient motor learning experience to achieve a skilled movement.

1. Introduction

The skill of walking, once established at an early age, rapidly becomes central to everyday life. Being able to confidently self-mobilize is key to the efficient and effortless performance of routine tasks and activities. The ability to walk ultimately allows individuals to maintain independence and autonomy over decisions regarding the activities they partake in, and when they do them. The physical and mental health benefits of remaining active are well-publicized and include prevention of chronic diseases such as diabetes, hypertension, osteoporosis, obesity and depression (Warburton et al., 2006).

Lower limb amputation can affect a person's confidence in their ability to walk. Limb amputation profoundly disrupts the neuromusculoskeletal system. The resultant sensory, structural and mechanical deficits have implications for the execution of normal daily activities under newly defined constraints. Individuals with unilateral, transtibial amputation of both vascular and traumatic etiologies spend less time walking on average during a day than matched individuals with no known impairments (Bussmann et al., 2004, 2008), highlighting the impediment to mobility and participation.

Increased stride-to-stride fluctuations have been observed in the movements of both the intact and prosthetic limbs of individuals with amputation during walking in comparison to able-bodied participants (Beurskens et al., 2014; Wurdeman et al., 2013a, 2013b). Variability is inherent in gait even in the absence of injury or pathology (Hausdorff et al., 1996; Stergiou and Decker, 2011). This is largely due to the neuromusculoskeletal system's multiple articulations and actuators that provide the human body with an abundance of degrees of freedom from which to coordinate an appropriate movement solution (Bernstein, 1967). The subtle fluctuations that exist within the well-orchestrated cyclical patterns of healthy locomotion may indeed be considered a mark of a skilled movement; the system has mastered the exploitation of its degrees of freedom and, importantly, has retained sufficient adaptability to enable performance to be maintained despite a continuously changing environment. Pathology could result in greater divergence in the movement patterns resulting in increased fluctuations, however, reflecting a less organized movement

---

* Corresponding author at: Biomechanics Research Building, University of Nebraska at Omaha, 6160 University Drive, Omaha, NE 68182-0860, USA.
E-mail addresses: jkent@unomaha.edu (J.A. Kent), nstergiou@unomaha.edu (N. Stergiou), swurdeman@hanger.com (S.R. Wurdeman).

http://dx.doi.org/10.1016/j.clinbiomech.2015.07.015

(Wurdeman et al., 2013b). Such alterations when walking have been associated with an increased risk of falls (Hausdorff, 2007; Lockhart and Liu, 2008).

Wurdeman et al. (2013b) reported significantly greater stride-to-stride fluctuations of the sound hip, sound knee and prosthetic ankle motion of individuals with transtibial amputation. Given the reduced activity levels of individuals with amputation, it is possible that these increased stride-to-stride fluctuations are due to limited task practice. Consistent with this proposition, Lin et al. (2014) reported a moderate negative correlation between physical activity and both step length and step width variability, measured by coefficient of variation, in individuals with lower limb amputation. It is possible that individuals who are more active afford their system more opportunity to resolve upon an optimized solution that incorporates the prosthesis, resulting in more organized movement patterns with less divergence.

It may therefore be expected that a relationship exists between physical activity and the fluctuations that occur in the joint movements of individuals with lower limb amputation. Therefore, the purpose of this study was to determine the relationship that exists between the activity level of an individual with lower limb amputation and stride-to-stride fluctuations during level walking. It was hypothesized that individuals with transtibial amputation who walk more in their average day would exhibit decreased stride-to-stride fluctuations in their lower limb joint motion and more organized movement patterns.

2. Methods

All procedures were approved by the university medical center and Veterans Affairs Institutional Review Boards.

2.1. Participants

Twenty-two participants (age 52.0 (SD 10.9) years, height 1.77 (SD 0.8) m, mass 101.6 (SD 19.3) kg) with unilateral transtibial amputation, recruited from local community clinics, gave informed consent to participate (Table 1). All were active community ambulators, classified as K3 or higher according to the Medicare Functional Classification Level (MFCL) system.

In accordance with the study inclusion criteria, all participants were able to walk non-stop for three minutes without walking aids. Individuals were excluded if they had a poor fitting prosthesis, ulcers on either the residual or intact limb, musculoskeletal or neuromuscular conditions affecting gait, or the inability to provide informed consent due to cognitive impairment.

2.2. Procedures

2.2.1. Step count

During an initial visit to the laboratory, following the consent process, an accelerometer-based activity monitor (Actigraph, Pensacola, FL, USA) was attached to the prosthetic pylon in order to monitor step count over a three week period. Participants were asked to proceed with their daily activities during this period with no other specific instructions given.

Table 1
Cohort anthropometrics and demographics.
Values expressed as mean (SD) unless otherwise stated.

Age (yrs)	Time since amputation (yrs)	Height (m)	Mass (kg)	Amputation etiology	N
52.0 (10.9)	9.1 (10.2)	1.77 (0.8)	101.6 (19.3)	Diabetes	5
				Vascular disease	2
				Trauma	13
				Cancer	1
				Infection (non-diabetic)	1

2.2.2. Joint angle motion

After three weeks, participants returned to the laboratory for detailed gait analysis, where the activity monitor was removed. Kinematic data were collected using a 12 camera optoelectronic motion capture system (60 Hz; Motion Analysis Corp., Santa Rosa, CA, USA). Participants wore a tight fitting uniform. Retro-reflective markers were attached superficial to the following locations on the pelvis and lower limbs bilaterally: anterior superior iliac spine, posterior superior iliac spine, greater trochanter, lateral mid-thigh, anterior distal thigh, laterally and medially on the knee joint line, tibial tuberosity, lateral mid-shank, lateral and medial malleoli, posterior and lateral calcaneus, dorsum of second metatarsal-phalangeal joint, and at the first and fifth metatarsal–phalangeal joints. Medial markers were removed following static calibration files to avoid impairing movement during walking (Celis et al., 2009) (see Supplementary Information for further detail).

Walking trials were conducted at a self-selected speed on a motorized treadmill (Bodyguard Fitness, St-Georges, QC, Canada). Walking speed was determined prior to the test. The belt velocity was gradually increased, initially in 0.5 mph (0.22 m/s) increments but reducing as the specific speed was determined. On receipt of verbal confirmation from the participant that a pace that could be maintained for 3 min had been reached, speeds 0.1 mph (0.04 m/s) faster and slower were checked. The subject walked at the chosen speed for a further minute to ensure that this speed was appropriate.

Participants performed two 3-minute walking trials at their self-selected walking speed separated by a minimum 1 minute rest. Only the first of the two trials was processed for each participant, unless an anomaly (e.g. a stumble, poor marker tracking realized in post-processing, etc.) occurred during the first trial, in which case the second was used.

Calibration trial data were used to construct lower limb models and reference positions for the left and the right limbs using Visual 3D v5 software (C-motion, Inc., Germantown, MD, USA). Sagittal plane lower limb joint kinematics were calculated for prosthetic and intact limbs.

2.2.3. Largest Lyapunov exponent

The largest Lyapunov exponent (λ) at each lower limb joint was calculated for each participant to quantify stride-to-stride fluctuations in walking (Wolf et al., 1985). Unlike linear variability statistics that assume that values extracted from time series data (e.g. peaks, peak timings) are not interrelated, fundamental to many non-linear techniques is the acknowledgment of dependencies across repetitions, such that every stride analyzed is related to those produced before and after. The examination of the relationships across successive steps provides insights related to control (Hausdorff, 2007). The λ specifically provides a measure of the exponential divergence over time of the trajectories associated with each repetition of the stepping motion. A λ value of 0 would indicate a perfectly repeating stepping pattern, that is, each repetition of the movement describes an identical movement trajectory; a phenomenon that equates to a complete lack of variability which has, thus far, not been observed in biological movement. Greater λ values are associated with greater divergence across the trajectories of a movement as it is repeated.

The λ was calculated for each joint of the bilateral lower extremities (Wolf et al., 1985). All of the time series were cropped to 110 strides; the minimum number attained by any participant during the 3 minute trial. The embedding dimension, calculated using the false nearest neighbor algorithm, was set to 7, and the time lag, calculated by the average mutual information algorithm set to 3 (Abarbanel, 1996). The number of time points to propagate before finding a new nearest neighbor, n, was set equal to 3 (Myers et al., 2009; Wolf et al., 1985), the maximum angle (from reference trajectory that a new nearest neighbor must reside in) was set to 0.3 radians (Wolf et al., 1985), the minimum scale length (minimum distance to selection of new nearest neighbor) was set to 0.0001 (Wolf et al., 1985), and the maximum scale length