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

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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 (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 (maximum distance to selection of new nearest neighbor) was set to 0.1 times the maximum length of the attractor (Wolf et al., 1985). Further and more detailed explanation on the calculation of λ can be found in our previous work (Wurdeman et al., 2013a, 2013b, 2014). A download- able version of the MATLAB code is available at http://www.unomaha.edu/college-of-education/biomechanics-core-facility/research/computer-codes.php.

Daily step count (DSC) was averaged over the three week period.

2.2.4. Statistical analysis

The relationships between DSC and λ were tested using a Pearson correlation with significance set at 0.05, with strength of relationship as defined by Cohen (1988).

3. Results

DSC ranged from 2497 to 8305 steps/day (mean 4581(SD 2032) steps/day) and self-selected treadmill walking speeds from 0.27 to 1.88 m/s (mean 0.84 (SD 0.40) m/s). There was a strong positive relationship between walking speed and step activity (r = 0.76, P b 0.001).

Significant, moderate negative correlations were found between DSC and λ of the motion of the intact ankle (r = 0.57, P = 0.005) and the prosthetic knee (r = 0.44, P = 0.038). We should, however, mention that after omission of a potential outlier (Grubb's test, significant at P = 0.05), this latter result becomes non-significant (r = 0.39, P = 0.069). The rest of the relationships investigated were weak and non-significant (Fig. 1).

4. Discussion

The aim of this work was to determine whether there is a relationship between daily physical activity and stride-to-stride fluctuations of lower limb joint motion for individuals with transtibial amputation. It was hypothesized that these variables would be negatively correlated, such that individuals who took more steps would exhibit lower λ values than more sedentary participants, as a result of increased task practice leading to improvements in motor organization. The λ was specifically calculated for its ability to provide further insight on the organization of the movement pattern by quantifying the underlying structure of variability of the movement produced, with regard to the divergence of movement trajectories over time.

The average DSCs across participants were wide-ranging and comparable to values previously reported in the literature for individuals with amputation of varied etiologies (Lin et al., 2014). Approximately two thirds of the participants (n = 14) would be classified as sedentary, having taken on average under 5000 steps per day (Tudor-Locke and Bassett Jr, 2004). The strong positive relationship between walking speed and step activity also corroborated previously published results (Lin et al., 2014).

The primary finding is a significant correlation in the sagittal movement between DSC and λ of the intact ankle and potentially of the knee of the affected limb, such that a greater activity level is associated with lower divergence at these joints. This supports the previous findings of Lin et al., and, importantly, isolates the joint movements that have contributed to the modest reductions in linear step length and step width variability that the authors reported (Lin et al., 2014). The results are consistent with the notion that increased stride-to-stride fluctuations represent a less healthy movement pattern, and that disorganized movement and reduced activity are related. It is unclear, however, whether a causative relationship exists, and if so, what is the direction of this relationship. Two opposing interpretations are prompted by these results.

First, and consistent with the basis of our original hypothesis, it is possible that a higher level of context-specific physical activity (walking) has resulted in improved gait dynamics, indicated by a decrease in λ at these joints. In regaining the ability to walk with a prosthesis, individuals are required to find new movement solutions that effectively integrate their biological and artificial subsystems. Our findings here may illustrate the result of learning having taken place. Further investigation by means of an intervention study targeting the more sedentary individuals could confirm or refute this supposition. Alternatively, the repetition of this work in a group of recreational walkers and healthy able-bodied controls might determine whether increased walking activity can lead to reduced stride-to-stride fluctuations in the absence of pathology.

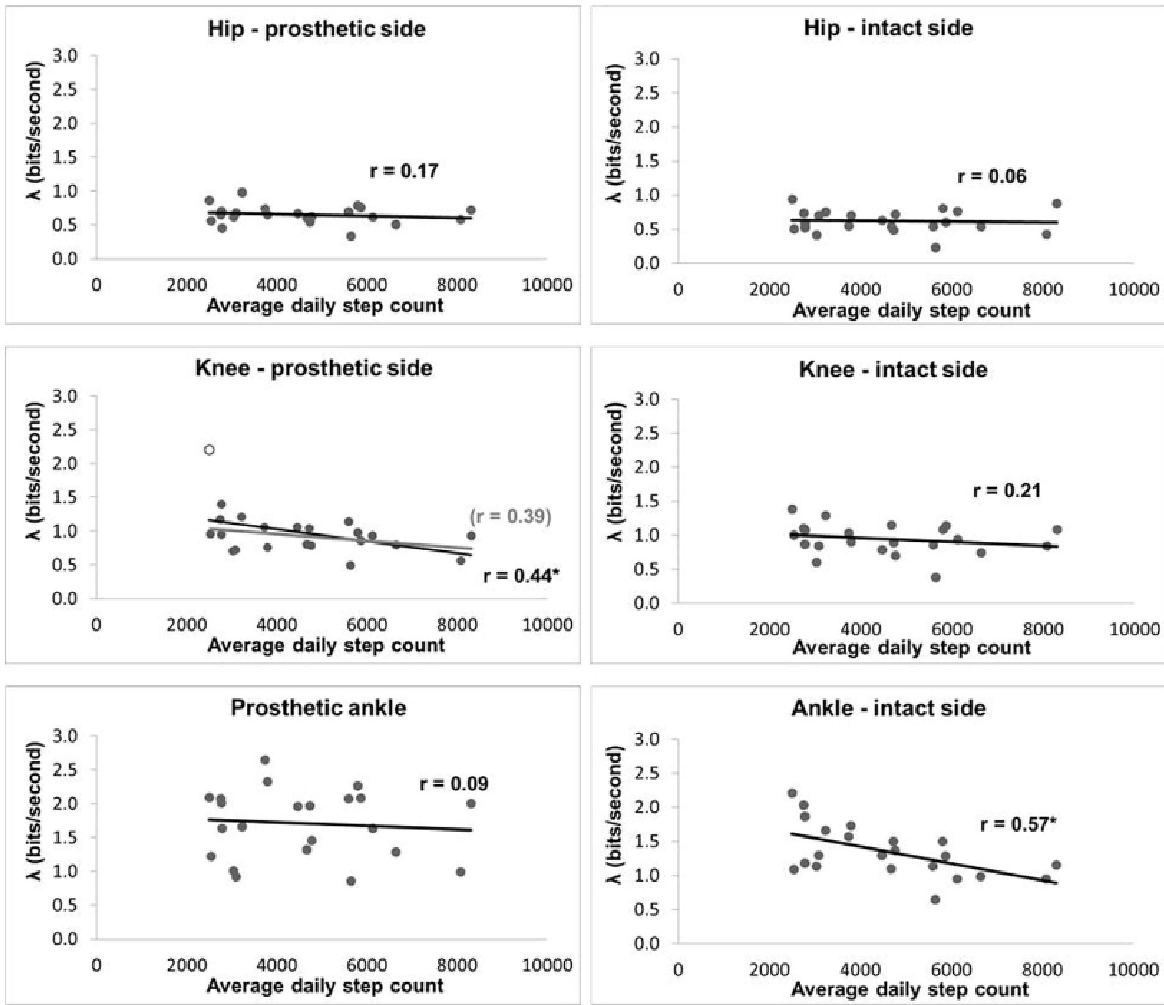

Fig. 1. Correlations between the largest Lyapunov exponent (λ) of sagittal plane lower limb joint angles during walking and the average daily step count collected over a three week period (*significant at $P < 0.05$). The r for knee of the prosthetic side is displayed with (black trendline/value) and without (gray trendline/value) a potential outlier (o).

Second, it is possible that, due to factors related to their health, their prosthesis or the combination of their artificial and biological systems, some individuals may be predisposed to a more divergent gait, which impedes physical activity. A prosthetic configuration that results in an unharmonious relationship between artificial and biological subsystems may naturally discourage the individual from prosthesis use. The negative correlation between prosthesis preference and λ previously reported by Wurdeman et al. (2013a) would support this.

The lack of a relationship between step activity and fluctuations at the prosthetic ankle may be a reflection of the inability of the artificial structure to imitate complex natural movement, regardless of the experience or capability of the user involved. It is of note that, should the potential outlier be in fact a representative result, significant relationships would be evident only at the most distal biological joint of each leg. In line with our first explanation, a lower divergence observed at the knee of the more practiced user may indicate that finer control has been developed to enable refined positioning of the artificial extremity as it contacts the ground; in essence, the body has more successfully adapted to the use of a tool, and can manipulate its motion to its advantage. Alternatively, it may be the case that particular components or alignments on an individual level result in an action that, although innately synthetic, is more compatible with the natural movement of the body, providing the user with a functional advantage at the outset, encouraging activity.

5. Conclusion

The results of our study may indicate that a relationship exists between daily step count and stride-to-stride fluctuations in the lower limb joint movements of individuals with unilateral, trans-tibial amputation. It remains to be established, however, whether increased activity reduces stride-to-stride fluctuations, or if a reduction in this divergence promotes increased activity.

Clinically, these opposing interpretations would prompt different rehabilitation strategies. The former would support encouraging a patient to increase their walking activity in order to improve their gait dynamics. In contrast, the latter would target interventions that may improve gait dynamics in order for an individual to remain active, for example, through providing the prosthesis that appears to most successfully minimize this divergence. Although our findings provide information of high clinical relevance, further investigation targeted at determining the nature of this relationship is required in order for our findings to inform decision making in clinical practice.

Conflict of interest statement

The authors have no financial or personal relationships with people or organizations that could have inappropriately biased or influenced this work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.clinbiomech.2015.07.015.

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