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The effects of walking speed on minimum toe clearance and on the temporal relationship between minimum clearance and peak swing-foot velocity in unilateral trans-tibial amputees

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Abstract

Background: Minimum toe clearance is a critical gait event because it coincides with peak forward velocity of the swing foot, and thus, there is an increased risk of tripping and falling. Trans-tibial amputees have increased risk of tripping compared to able-bodied individuals. Assessment of toe clearance during gait is thus clinically relevant. In able-bodied gait, minimum toe clearance increases with faster walking speeds, and it is widely reported that there is synchronicity between when peak swing-foot velocity and minimum toe clearance occur. There are no such studies involving lower-limb amputees.
Objectives: To determine the effects of walking speed on minimum toe clearance and on the temporal relationship between clearance and peak swing-foot velocity in unilateral trans-tibial amputees.
Study design: Cross-sectional.
Methods: A total of 10 trans-tibial participants walked at slow, customary and fast speeds. Minimum toe clearance and the timings of minimum toe clearance and peak swing-foot velocity were determined and compared between intact and prosthetic sides.
Results: Minimum toe clearance was reduced on the prosthetic side and, unlike on the intact side, did not increase with walking speed increase. Peak swing-foot velocity consistently occurred (~0.014 s) after point of minimum toe clearance on both limbs across all walking speeds, but there was no significant difference in the toe–ground clearance between the two events.
Conclusion: The absence of speed related increases in minimum toe clearance on the prosthetic side suggests that speed related modulation of toe clearance for an intact limb typically occurs at the swing-limb ankle. The temporal consistency between peak foot velocity and minimum toe clearance on each limb suggests that swing-phase inter-segmental coordination is unaffected by trans-tibial amputation.

Clinical relevance

The lack of increase in minimum toe clearance on the prosthetic side at higher walking speeds may potentially increase risk of tripping. Findings indicate that determining the instant of peak swing-foot velocity will also consistently identify when/where minimum toe clearance occurs.

Keywords

Unilateral trans-tibial amputee, gait, gait events, toe clearance, walking speed

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Background

Minimum toe clearance (MTC) during overground walking is defined as the local minimum in separation between the ground and the toes region of the forward swinging foot. The risk of tripping, which is the predominant cause of falls during ambulation,[1] is highest at the point of MTC.[2] This results from a combination of the proximity of the swing foot to the ground, the high velocity of the swinging foot, and the forward-travelling centre of mass being in front of the base of support.[3] Swing-foot velocity will increase with increasing walking speed, and previous

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research in able-bodied gait has shown that MTC also increases at faster walking speeds,[4] thereby increasing safety margins between the foot and the floor. The instant of peak forward velocity (PFV) of the swinging foot has been reported to coincide with MTC,[3] although empirical data to support this assertion were not presented. Numerous published studies allude to this previous study,[2,5,6] but, as with the original study, they do not present supporting data. No previous studies have investigated whether the relationship between PFV and MTC is affected by changes in walking speed. Nor have they investigated whether the relationship between PFV and MTC in unilateral transtibial amputee (UTA) gait is the same as it is in able-bodied gait or whether instead UTAs display differing temporal relationships between PFV and MTC on the intact and prosthetic limbs.

UTAs have been shown to have a higher risk of falls than age-matched, able-bodied controls.[7,8] This increased risk may partly be due to having lower MTC on the prosthetic side compared to intact side[9–11] and/or exhibiting increased MTC variability on both the intact and prosthetic limbs.[10] UTAs have altered gait kinematics and kinetics (when compared to able-bodied individuals) due to the mechanical constraints imposed on them by their prosthesis.[12–14] These constraints result in reduced walking speeds and increased inter-limb asymmetry compared to able-bodied individuals.[15] Furthermore, the compensatory intact-limb stance-phase power generation at the hip and ankle increase with increases in speed.[16] As a result of such asymmetries and/or compensatory biomechanical adaptations, the synchronicity between PFV and MTC reported (assumed) in able-bodied gait may not be present in UTAs.

The primary aim of this study was to determine the effects of changes in walking speed on intact- and prosthetic-limb MTC in UTAs during overground ambulation. A secondary aim was to establish whether PFV was synchronous with MTC for the intact and prosthetic limbs and whether the level of synchronicity was affected by changes in walking speed.

Methods

A total of 10 physically active male UTAs (mean ± standard deviation (SD) age = 48 ± 11.7 years, mass = 86 ± 17.7 kg, height = 1.78 ± 0.06 m) took part, each giving written informed consent prior to their involvement. All had undergone amputation at least 2 years prior to participation (mean = 10.8 ± 12.4 years, range = 2–43 years), and all had used their current prosthesis for at least 6 months (mean = 1.6 ± 1.2 years). All participants habitually used an *Esprit* foot (Chas. A. Blatchford and Sons Ltd, Basingstoke, UK). The study was conducted in accordance with the tenets of the Declaration of Helsinki, and approval was gained from the Institutional Committee for Ethics in Research.

Kinematic and ground reaction force (GRF) data were recorded at 100 Hz and 400 Hz, respectively, using an eight-camera motion capture system (Vicon MX, Oxford, UK) and two force platforms (surface area: 508 mm × 464 mm; AMTI, Watertown, MA, USA) while participants completed overground walking trails along a flat and level 8-m walkway. The force platforms were situated side by side approximately half way along the walkway, that is, approximately 4 m from where participants initiated gait to begin the trial. Trials were completed at three different speed levels: ‘customary’, ‘slow’ and ‘fast’. Due to the methodological limitations associated with speed-controlled studies and the difficulty in generalising findings from such studies to the natural environment,[17] we decided not to control walking speed. Instead, participants were instructed to walk ‘at their normal walking speed’, ‘slowly’ and ‘as fast as comfortably possible’. Participants completed trials at each speed until 20 ‘clean’ contacts with either force platform had been made with each foot (20 trials × 3 speeds × 2 limbs = 120 PFV/MTC events). A ‘clean’ contact was defined as one where the entire foot was placed onto a force platform without any visible targeting or change in step length or cadence. Only MTC events which occurred while the contralateral foot was in contact with one of the force platforms were used in subsequent analyses. We focussed our analysis on gait cycles occurring over the platform as this ensured that participants were walking at a steady-state walking speed when MTC was determined. This was important because of the analysis of speed effects.

During data collection, participants wore their own flat-soled shoes and ‘lycra’ shorts. Spherical, retro-reflective markers were placed bilaterally over the acromion processes, iliac crests, greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, heel, medial and lateral aspect of the mid-foot, first and fifth metatarsal heads and above the second toe (and corresponding locations on the prosthetic limb). Markers were also placed on the sternal notch, xiphoid process and C7 and T8 vertebrae. A headband was used to mount four head markers, and plate-mounted 4-marker clusters were worn on the thighs and shanks, while a skin-mounted 4-marker cluster was attached about the sacrum. Following ‘subject’ calibration, the acromion, knee and ankle markers were removed.

Labelling and gap filling of marker trajectories were undertaken within Workstation software (Vicon, Oxford, UK). The resultant C3D files were then exported to Visual3D motion analysis software (C-Motion, Germantown, MD, USA), where a nine-segment 6-degree-of-freedom (DoF) model of each participant[18] was constructed. More details regarding the data collection and processing methodology can be found in our earlier report.[19] Virtual landmarks were created at the antero-inferior end point of both shoes (shoe tip) and

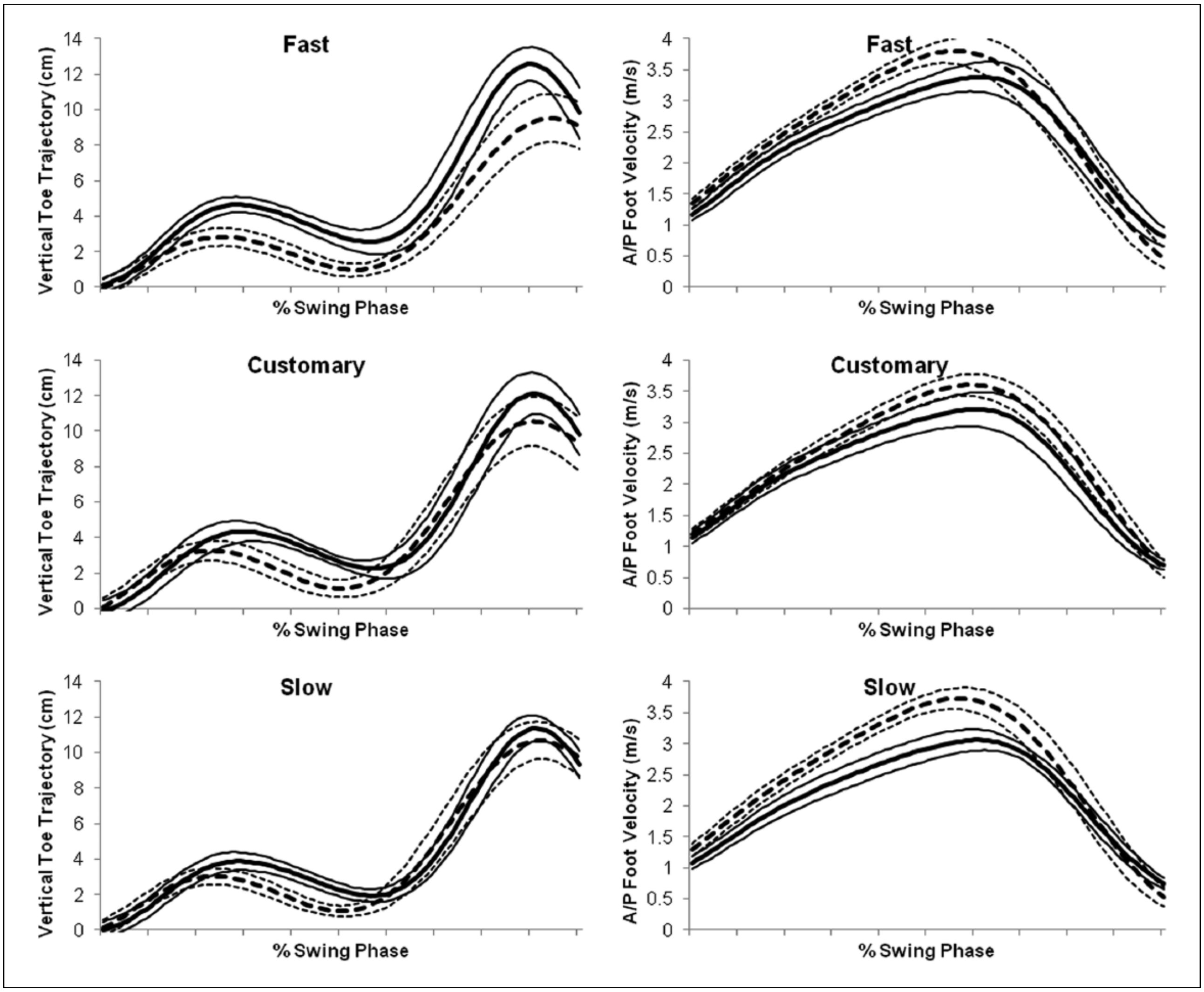

Figure 1. Ensemble mean ± SD swing phase vertical toe trajectory (left-hand column) and A/P foot velocity (right-hand column) for the intact (solid lines) and prosthetic (dashed lines) limbs for one participant at slow, customary and fast walking speeds.
SD: standard deviation; A/P: anteroposterior.

embedded within the local coordinate system of each foot.[10,20] Kinematic and GRF data were filtered using a fourth-order, zero-lag Butterworth filter with a 6-Hz cut-off. Initial contact (IC) and toe-off (TO) were defined as the instants at which the vertical component of GRF first went above or below 20 N, respectively. Due to equipment failure, there were no GRF data recorded for two participants; therefore, for these, IC and TO were defined using kinematic data: IC was defined as the instant of contralateral limb peak hip extension[21] and TO as the instant of peak posterior displacement of the ipsilateral toe marker relative to the pelvis.[22] Swing phase was defined from the instant of TO until ipsilateral IC.

The following parameters were determined: the instants of intact- and prosthetic-limb PFV, the instants of intact- and prosthetic-limb MTC and toe–ground clearance at intact- and prosthetic-limb PFV and MTC. The instant of PFV was defined as the point of maximal velocity in the direction of travel (anteroposterior (A/P)) of the foot-segment centre of mass during swing and was determined automatically within Visual3D. The instant of MTC was defined as the point of the local minimum of the vertical component in shoe-tip trajectory during mid-swing and was determined manually by examining the shoe-tip trajectory of each trial (see Figure 1). We used this 'manual' approach to ensure that the local minima in toe–ground clearance that occur at or just after TO would not be identified in error, which might have been the case if we had determined MTC automatically. Toe–ground clearance values at PFV and MTC were determined as the height of shoe tip above the ground at each event.

Table 1. Mean (SD) walking speeds, temporal difference between PFV and MTC events and toe–ground clearance at PFV and MTC.

Walking speed (ms^{-1})	**Limb**	**Temporal difference[a] (s)**	**Range (s)**	**95% levels of agreement (s)**	**Toe clearance at PFV (cm)**	**Toe clearance at MTC (cm)**
Overall	Intact	−0.015 (0.011)	−0.04/+0.01	−0.037/+0.006	2.65 (0.76)	2.46 (0.87)
	Prosthetic	−0.012 (0.010)	−0.04/+0.05	−0.033/+0.008	1.21 (0.71)	1.10 (0.66)
Slow: 0.93 (0.12)	Intact	−0.015 (0.011)	−0.05/0	−0.037/+0.006	2.49 (0.78)	2.28 (0.87)
	Prosthetic	−0.012 (0.010)	−0.04/+0.03	−0.031/+0.007	1.22 (0.73)	1.11 (0.69)
Customary: 1.13 (0.17)	Intact	−0.015 (0.011)	−0.04/0	−0.038/+0.007	2.70 (0.79)	2.52 (0.90)
	Prosthetic	−0.011 (0.011)	−0.04/+0.05	−0.033/+0.010	1.20 (0.71)	1.09 (0.68)
Fast: 1.36 (0.27)	Intact	−0.016 (0.010)	−0.04/+0.01	−0.036/+0.005	2.77 (0.74)	2.57 (0.85)
	Pros	−0.014 (0.011)	−0.04/+0.02	0.035/+0.007	1.22 (0.74)	1.10 (0.64)

SD: standard deviation; PFV: peak forward velocity of the swinging foot; MTC: minimum toe clearance.
A negative temporal difference indicates that PFV occurred after MTC.

Statistical analysis

A 'Limits of Agreement' (LOA) analysis[23] and 95% confidence intervals established agreement between the instants of when PFV and MTC events occurred. This analysis determined the mean positive or negative temporal difference (bias) between the timings of the two events (agreement) and also the period of time before or after MTC in which 95% of PFV events occurred (precision/repeatability). The normality (or otherwise) of the data was determined using a Shapiro–Wilk test. Toe–ground clearances were compared using repeated measures analysis of variance (ANOVA) with limb (prosthetic and intact), event (PFV and MTC) and speed level (slow, customary and fast) as between-factors. Post hoc analyses were conducted using a Tukey's honestly significant difference (HSD) test. The alpha level was set at 0.05.

Results

Mean walking speeds for the slow, customary and fast levels were $0.93 \pm 0.12\ ms^{-1}$, $1.13 \pm 0.17\ ms^{-1}$ and $1.36 \pm 0.27\ ms^{-1}$, respectively (range = $0.73–1.77\ ms^{-1}$). In total, 1200 PFV and 1200 MTC events (600 each for intact and prosthetic limbs) were analysed. Data were normally distributed ($p > 0.05$).

Speed-related alterations in MTC

MTC was significantly affected by walking speed ($p = 0.011$) so that clearances at the fast speed were significantly higher than those at the slow speed ($p = 0.010$), although a speed-by-limb interaction ($p = 0.004$) indicated that only the speed-related increases on the intact limb were significant (Table 1). There were no significant differences in the toe–ground clearance values at MTC and PFV across all speeds ($p = 0.38$). MTC was significantly lower ($p < 0.001$) on the prosthetic limb, and post hoc analysis indicated that differences between limbs were significant at all speeds (slow: 1.11 ± 0.69 cm; customary: 1.09 ± 0.68 cm; fast: 1.10 ± 0.64 cm) compared to the intact limb (slow: 2.28 ± 0.87 cm; customary: 2.52 ± 0.90 cm; fast: 2.57 ± 0.85 cm).

Synchronicity in PFV and MTC

The agreement (synchronicity) between the timing of PFV and MTC at each walking speed level and the average agreement across all speeds are shown for the intact and prosthetic limbs in Table 1. On the intact limb, PFV occurred 0.015 ± 0.011 s after MTC, and the 95% LOA between PFV and MTC was −0.037 s to +0.006 s. On the prosthetic limb, PFV occurred 0.012 ± 0.010 s after MTC, and the 95% LOA between PFV and MTC was −0.033 s to +0.008 s.

Discussion

The aim of this study was to determine how alterations in walking speed affected MTC in UTAs during overground ambulation. A secondary aim was to establish whether alterations in walking speed affected the temporal relationship between PFV and MTC. The results indicate that MTC increased at higher walking speeds on the intact limb but was unaffected by changes in speed on the prosthetic limb. Furthermore, irrespective of limb, there was a small and consistent temporal difference (bias) between when PFV and MTC occurred that was unaffected by walking speed. Finally, the results also indicate that MTC was significantly reduced on the prosthetic limb compared to the intact limb across all speeds.

The increase in intact-side toe clearance with increasing walking speed is similar to the speed-related increases reported in able-bodied individuals.[4] It has been reported previously that some degree of inter-limb asymmetry in toe clearance occurs in older able-bodied adults.[24] The authors noted that the inter-limb asymmetry in toe clearance was associated with step time asymmetry, that is, the limb with the shorter step time and higher swing-foot velocity had higher toe–ground clearance. They suggested that increased safety margins required at faster swing-foot speeds may be driving the asymmetry. Such speed–accuracy considerations cannot explain toe-clearance inter-limb asymmetries in UTAs who typically present spatially longer steps on the prosthetic limb than on the intact limb as well as higher swing-foot velocities on the prosthetic side (as highlighted in Figure 1). If speed–accuracy considerations were the primary driver of such differences, it would be expected that higher clearances would occur on the prosthetic side at all walking speeds. The finding (in this study) that toe–ground clearance on the prosthetic side did not increase with speed but did on the intact side indicates that step time/length asymmetry is not the driver of UTA toe-clearance asymmetries. The fact that toe–ground clearance increased with speed on the intact side but not on the prosthetic side suggests that some level of active, central motor control of the swinging foot was present on the intact limb and absent on the prosthetic limb. In the present study, the magnitude of speed-related changes in toe–ground clearance was around 2–3 mm. Only minimal dorsiflexion (~1°) would be required to affect such changes. It would seem apparent therefore that the active control on the intact limb occurred at the ankle, which would explain why such control was not evident on the prosthetic side.

The mean temporal difference between when PFV and when MTC occurred was small – approximately 0.014 ± 0.01 s across both limbs and across all speeds. PFV occurred consistently after MTC, indeed only 7 of 1200 PFV events occurred prior to the corresponding MTC event. In other words, the temporal relationship between PFV and MTC was unaffected by changes in walking speed and was the same for both the prosthetic and intact sides. This invariance suggests that swing phase inter-segmental coordination is the same for both limbs. It also suggests that during swing, the lower limbs act as simple mechanical pendulums, and thus, toe–ground clearance is, at least partially, a result of how the entire limb swings about the hip rather than being solely/largely controlled by swing-limb ankle and/or knee flexion. Hence, as well as its relevance to trips and falls, analysis of MTC metrics also provides insights into underlying neural control strategies and coordination patterns.

In the study by Winter,[3] it was highlighted that PFV and MTC were synchronous. However, no empirical data were presented to support this contention, and in addition, the sampling rate of the kinematic analysis was not detailed. It is reasonable to infer that the video-based methodology used to collect the kinematic data in Winter's[3] study would have been sampled at a lower rate (likely ~ 30 Hz) than that used in the present study – due to the limitations in video technology at that time. The lower temporal resolution may well have given the appearance of absolute synchronicity (no temporal difference) between PFV and MTC. The present study, which used a sampling rate of 100 Hz, demonstrated that MTC occurs, on average, slightly (i.e. just over one sampling frame) before PFV. This small but consistent temporal offset between PFV and MTC likely explains the slight (non-significant) difference in toe–ground clearance between each event (Table 1). It is important to emphasise that the temporal relationship between PFV and MTC (PFV consistently occurring after MTC) was invariant across limbs and across walking speeds. Furthermore, although there was no significant difference in the toe–ground clearance values at PFV and MTC, toe–ground clearance was on average 1–2 mm higher at PFV than at MTC. We thus suggest that when adopting the approach of using PFV to identify the instance of when MTC occurs, an offset of +0.014 s should be applied. That is, once instant of PFV is identified, the toe–ground clearance value 0.014 s sooner in swing should be determined as the point of MTC.

The significantly lower clearance on the prosthetic side compared to the intact side corroborates previous findings.[9–11] In a current sister study, we argue that the differences in MTC between the intact and prosthetic limbs is mainly due to having greater intact-limb MTC (compared to values reported in the literature for able-bodied individuals), rather than the prosthetic limb having reduced MTC.[11] Having greater clearance on the intact side is likely to be, at least to some extent, a result of UTAs typically presenting reduced residual-knee flexion during the loading response of early stance,[11,25,26] which would raise the height of the swing-limb hip. While reduced stance-phase residual-knee flexion likely contributed, in the present study, to the differences in MTC between sides, it is important to note that prosthetic-limb MTC (~1.1 cm) is lower than that previously reported for able-bodied adults (1.8–1.9 cm)[27,28] and is also slightly lower than what we report (in our sister study) for the prosthetic limb in a larger group of amputees (1.9 cm).[11] In the present study, all amputees used the same type of prosthetic foot (Esprit), whereas in our other study,[11] participants used a range of foot types. This suggests that the type of prosthetic foot and, perhaps more particularly, the way it is set up will have a bearing on prosthetic-limb MTC. Indeed, in our other study, we show that prosthetic-limb MTC is increased when participants switched from using their habitual prosthetic foot to using a foot with a hydraulically articulating 'ankle' attachment that allowed the foot to be relatively dorsiflexed at TO and throughout swing.[11]

Conclusion

The lack of walking speed–related toe–ground clearance changes on the prosthetic side may potentially increase UTAs' risk of tripping at faster walking speeds. The lack of change on the prosthetic side (but increase in toe clearance with speed on the intact side) also suggests that speed-related modulation of toe–ground clearance for an intact limb typically occurs at the ankle. The timing of when PFV occurred was virtually synchronous with MTC. The consistent and minimal temporal difference between the two events was invariant across speed levels and across limbs. This temporal consistency suggests that both lower limbs act as simple mechanical pendulums during swing. Finally, the consistent and minimal temporal differences between events, regardless of speed and limb, indicate that identifying the instant of peak swing-foot velocity could be implemented in automated processing procedures to determine the point of MTC.

Conflict of interest

The authors declare that there is no conflict of interest.

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