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# The effects of laterality on obstacle crossing performance in unilateral trans-tibial amputees

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ABSTRACT

*Background:* Unilateral trans-tibial amputees have bilaterally reduced toe clearance, and an increased risk of foot contact, while crossing obstacles compared to the able-bodied. While the able-bodied tend to lead with a 'preferred' limb it is equivocal whether amputees prefer to lead with the intact or prosthetic limb. This study determined the effects of laterality, compared to side of amputation, on amputees' obstacle crossing performance. To help understand why laterality could affect performance we also assessed knee proprioception for both limbs.

*Methods:* Foot placement and toe clearance parameters were recorded while nine amputees crossed obstacles of varying heights leading with both their intact and prosthetic limbs. Joint-position sense was also assessed. Participants self-reported which limb was their preferred (dominant) limb.

*Findings:* There were no significant differences in foot placements or toe clearance variability across lead-limb conditions. There were no significant differences in toe clearance between intact and prosthetic lead-limbs ($p = 0.28$) but toe clearance was significantly higher when amputees led with their preferred compared to non-preferred limb ($p = 0.025$). There was no difference in joint-position sense between the intact and residual knees ($p = 0.34$) but joint-position sense tended to be more accurate for the preferred, compared to non-preferred limb ($p = 0.08$).

*Interpretation:* Findings suggest that, despite the mechanical constraints imposed by use of a prosthesis, laterality may be as important in lower-limb amputees as it is in the able bodied. This suggests that amputees should be encouraged to cross obstacles leading with their preferred limb.



## 1. Introduction

In able-bodied adults, lead-limb toe clearance during obstacle crossing is typically reported to be around 12 cm but is about half that for amputees (Buckley et al., 2013), regardless of whether leading with the intact or the prosthetic limb (Hill et al., 1997). Irrespective of which limb they lead with, unilateral trans-tibial amputees (UTAs) make ten times as many errors than able-bodied individuals when trying to avoid obstacles during treadmill locomotion (Hofstad et al., 2006; Hofstad et al., 2009); due to bilaterally delayed response times, indicative of central nervous system (CNS) reorganisation (Hofstad et al., 2009). This reduced toe clearance and CNS reorganisation suggest that UTAs will have a higher trip risk when crossing obstacles compared to able-bodied individuals, and this higher trip risk may explain their increased incidence of falling (Miller et al., 2001). Depending on a particular physical therapist's or prosthetist's opinion, leading with either the prosthetic or intact limb can be advocated during amputee rehabilitation, as both approaches can be justified using evidence from published research. For instance, an intact limb lead could be advocated because, when leading with the prosthetic limb, UTAs are unable to increase toe clearance by dorsiflexing the foot during swing (Hill et al., 1997), have knee flexion limited by the posterior edge of the socket (Hill et al., 1997) and are mechanically constrained by the need to minimise residual knee loading during the initial landing period following crossing (Buckley et al., 2013). Conversely, leading with the prosthetic limb may be advocated because the lack of active 'ankle' control and power generation at the prosthetic (support) limb (Barnett et al.) means that intact (swing) limb toe clearance is reduced in comparison to that in the able-bodied. So, does it matter which limb UTAs lead with when they step over an obstacle?

When crossing obstacles, the able-bodied tend to lead with a 'preferred limb'. This is likely due to laterality; which can be defined as a preference for favouring one limb over the other to accomplish fine motor tasks and manifests itself as 'handedness' in the arms or 'footedness' in the legs. However, there is equivocation in the literature regarding which is UTAs' preferred lead-limb when crossing obstacles (Hill et al., 1997; Barnett et al.; Vrieling et al., 2007). UTAs have been reported to either demonstrate no preference (Hill et al., 1997), to prefer

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leading with the prosthetic limb (Vrieling et al., 2007), or conversely with the intact limb (Barnett et al.). In amputee gait research, there tends to be a focus on comparing between the intact and prosthetic limbs [e.g. see Vrieling et al., 2007, Hofstad et al., 2006, Hofstad et al., 2009,Vrieling et al., 2007] and hence laterality is ignored, presumably because it is assumed that it is outweighed by the mechanical differences between limbs. Perhaps this approach is not always appropriate. Therefore this study investigated whether limb laterality has an effect on the everyday locomotive task of obstacle crossing. Specifically, the study determined the effects of laterality, compared to side of amputation, on obstacle crossing performance in UTAs. We postulated that, if limb laterality is preserved after lower-limb amputation, obstacle clearance metrics would indicate improved performance when leading with the preferred versus non-preferred limb; with less/minimal difference between the intact and prosthetic limbs. If, however, laterality is mitigated by the mechanical constraints imposed by the prosthesis then obstacle clearance metrics would indicate improved performance when leading with the intact versus prosthetic limb; with less/minimal difference between the preferred and non-preferred limbs. To gain insight as to why laterality could affect performance we also assessed knee proprioception for both limbs and determined if proprioception is likewise governed by laterality, rather than by side of amputation. We postulated again that, if limb laterality is preserved after lower-limb amputation, proprioception would be more accurate on the preferred versus non-preferred limb. If, however, laterality is mitigated by amputation then proprioception would be more accurate on the intact versus prosthetic limb.

## 2. Methods

Nine, otherwise healthy, UTAs (mean (SD) age 48.3 (13.7) years; height 1.78 (0.09) m; mass 86.7 (9.4) kg; time since amputation 20.1 (15.3) years, range 5–51 years, one female), took part in the study. All had undergone amputation as a result of trauma and were described as being at least K3 on the Medicare scale by their prescribing clinician. Each gave written informed consent prior to participation. Ethical approval was obtained from the institutional ethics committee.

### 2.1. Obstacle crossing performance

Participants started with their back turned to an 8 m walkway during which time one of the three obstacles (3, 7 or 10 cm high, 51 cm wide, 0.5 cm deep) was placed approximately 3 m from the participant. To prevent a 'learning effect' regarding foot placement no specific starting point was defined. Participants were instructed to then turn around and to walk at their freely chosen speed along the walkway stepping over the obstacle as they went. Each participant completed three trials at each obstacle height. Obstacle height was randomised across trials. Participants completed one set of nine trials leading with the intact limb and another set leading with the prosthetic limb. Lead-limb order was counterbalanced across participants. Following completion of all trials, each participant was asked which limb they had preferred to lead with during the obstacle crossing trials and were also asked which limb, prior to amputation, they 'would have kicked a ball with'. Foot placement and clearance variables were determined. Toe clearance was defined as the vertical separation between the antero-inferior tip of the shoe (De Asha and Buckley, 2014) and top of the obstacle. Toe clearance variability was defined as the standard deviation of toe clearance across repeated trials for each height and lead-limb condition. Trail foot placement before, and lead foot placement after, the obstacle were the horizontal distances between the trail foot toe and the lead foot heel, respectively, and the obstacle. Crossing speed was the average forward velocity of the whole-body centre of mass during the crossing step.

*Knee proprioception* was assessed as joint-position sense (Barrack et al., 1983). Active angle reproduction was determined whilst participants lay supine on a 'physio' couch. A foam wedge was placed under the thigh so that the knee was raised with the shank and foot hanging freely over the edge of the coach, and the knee flexed by approximately 70°. Participants were asked to neither assist nor resist the movement, while an experimenter passively extended the 'relaxed' knee at a subjectively judged slow speed (approximately 10 to 15° per second) until the experimenter, a qualified and experienced physiotherapist, estimated the target angle (knee flexion angle of approximately 40°) had been reached. Participants were instructed to hold the knee isometrically in the target position for about 4 s. The experimenter then re-supported the shank and returned the 'relaxed' limb to the resting position at approximately 10° to 15° per second. After a 4 s pause, the participant was instructed to extend the knee to the perceived target angle and to hold that position for 4 s before returning the limb to the start position (Barrack et al., 1983). The above procedure was repeated five times with each limb. Participants wore their prosthesis throughout. Joint-position sense was defined as the error between the target knee angle and the reproduced knee angle, and was determined as the mean scalar difference (across trials) between target and response angles (Barrack et al., 1983).

### 2.2. Data processing and statistics

For both protocols (*obstacle crossing*, *knee proprioception*) segmental kinematic data were recorded at 100 Hz using an eight camera motion capture system (Vicon MX, Oxford, UK) and processed within Visual 3D software (C Motion, Germantown, MD, USA) using the approach previously described (Buckley et al., 2013; De Asha et al., 2013). The antero-inferior tip of each shoe was defined using a digitizing wand (C Motion, Germantown, MD, USA) and embedded within the local coordinate system of each foot segment. The whole-body centre of mass was

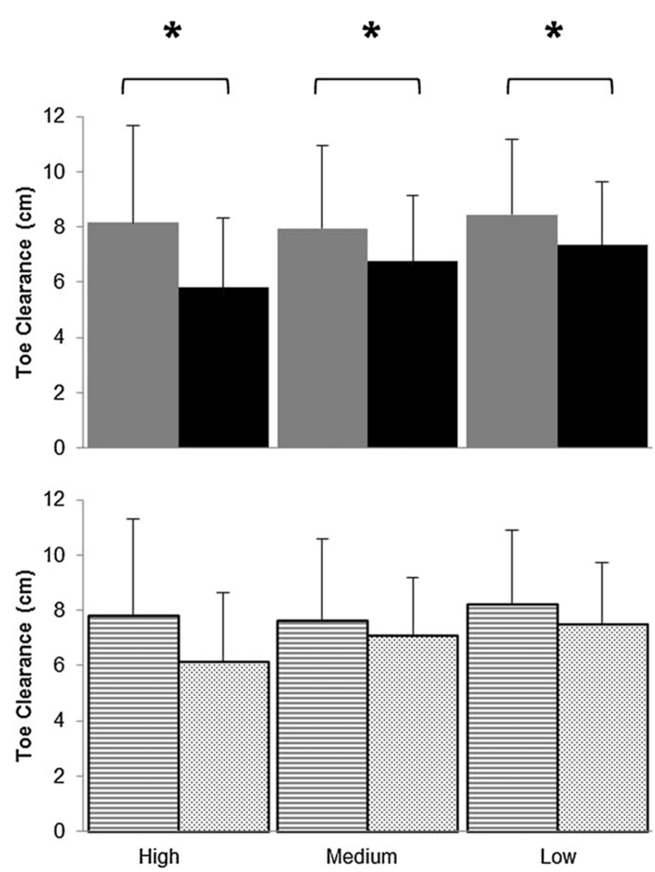


**Fig. 1.** Group mean (SD) toe clearance while crossing high, medium and low obstacles leading with preferred (grey) and non-preferred limb (black, *top panel*) and leading with the intact (stripes) and prosthetic limb (dots; *bottom panel*). Statistically significant differences between limbs are highlighted by *($p < 0.05$).

defined as the weighted average of a nine-segment model which incorporated head, thorax/abdomen, pelvis, thighs, shanks and feet.

Joint-position data were analysed using paired *t*-tests. Obstacle crossing data were analysed using repeated measures analyses of variance (ANOVA) with lead-limb (intact and prosthetic, or preferred and non-preferred: separate ANOVA for each lead-limb comparison) and obstacle height (high, medium, low) as factors. Post-hoc tests were completed using a Tukey HSD test. The alpha level was set at 0.05.

## 3. Results

Five participants preferred to lead with their intact limb, and four preferred to lead with their prosthetic limb. All stated that their preferred lead-limb was the same limb they would have kicked a ball with, prior to their amputation.

### 3.1. Obstacle crossing performance

When comparing between the intact and prosthetic limbs there was no significant effect of lead-limb ($p = 0.28$) or obstacle height ($p = 0.053$) on mean toe clearance. When comparing between preferred and non-preferred limbs there was no significant effect of obstacle height ($p = 0.053$) but there was a significant effect of lead-limb ($p = 0.025$) on toe clearance in that toe clearance was higher when leading with the preferred limb (Fig. 1). Irrespective of whether comparing between intact and prosthetic or between preferred and non-preferred lead-limbs, there were no significant effects of lead-limb on toe clearance variability or foot placements ($p > 0.25$, Table 1). In both lead-limb comparisons, foot placements were unaffected by obstacle height ($p > 0.15$) but crossing speed increased as obstacle height was reduced ($p = 0.030$); although post-hoc analysis indicated no significant differences between individual heights. Crossing speed was lower when leading with the prosthetic compared to intact limb ($p = 0.002$) but there was no difference between the preferred and non-preferred lead-limb conditions ($p = 0.17$). There were no significant interaction effects between lead-limb and obstacle height on any of the variables.

### 3.2. Knee proprioception

When comparing between the intact and residual knees, there were no significant differences in joint-position sense ($p = 0.34$). When comparing between preferred and non-preferred limbs, there was a (non-significant) trend ($p = 0.08$) for the preferred limb knee to have more accurate joint-position sense (Table 2).

## 4. Discussion

The purpose of this study was to investigate whether laterality had an effect on obstacle crossing performance in UTAs. There were no significant differences in toe clearance between intact and prosthetic limb leads but clearance was significantly higher when amputees led with their preferred limb. This increase in toe clearance occurred without any change in toe clearance variability, foot placements or in crossing speed. For all participants the preferred lead-limb was the limb they would have kicked a ball with prior to their amputation (and in four of the nine participants this was the prosthetic limb). The results also indicated that there was no difference in joint-position sense between the intact and residual knees but there was a trend ($p = 0.08$) for improved knee joint-position sense for the preferred compared to non-preferred limb. These findings therefore suggest that laterality is preserved in the limbs after amputation. Many UTAs indicate that they have the sensation that they can still wiggle their toes on the amputated side i.e. the toes of their phantom limb (Ramachandran and Hirstein, 1998). This

**Table 1**
Group mean (SD) foot placement and toe clearance parameters during obstacle crossing for when leading with intact versus prosthetic limbs and for when leading with the preferred versus non-preferred limbs. Statistically significant differences are highlighted in bold.

| | Lead-limb | Obstacle height | | | *P* value |
|---|---|---|---|---|---|
| | | High | Medium | Low | |
| Toe-obstacle clearance variability (cm) | Preferred | 1.21 (0.83) | 1.15 (0.52) | 1.18 (0.81) | Limb 0.55<br>Height 0.60<br>Int. 0.76 |
| | Non-preferred | 1.37 (0.91) | 1.14 (0.54) | 1.50 (0.60) | |
| | Intact | 1.69 (0.80) | 1.10 (0.45) | 1.39 (0.87) | Limb 0.25<br>Height 0.60<br>Int. 0.11 |
| | Prosthetic | 1.07 (0.75) | 1.21 (0.59) | 1.25 (0.51) | |
| Crossing speed ($ms^{-1}$) | Preferred | 0.95 (0.13) | 0.95 (0.14) | 0.99 (0.11) | Limb 0.17<br>**Height 0.030**<br>Int. 0.18 |
| | Non-preferred | 0.99 (0.10) | 0.98 (0.08) | 1.00 (0.08) | |
| | Intact | 1.01 (0.09) | 1.00 (0.10) | 1.02 (0.08) | **Limb 0.002**<br>**Height 0.030**<br>Int. 0.68 |
| | Prosthetic | 0.93 (0.11) | 0.94 (0.13) | 0.97 (0.11) | |
| Lead foot placement beyond the obstacle (m) | Preferred | 0.22 (0.05) | 0.22 (0.05) | 0.23 (0.04) | Limb 0.71<br>Height 0.46<br>Int. 0.53 |
| | Non-preferred | 0.23 (0.04) | 0.23 (0.05) | 0.22 (0.05) | |
| | Intact | 0.22 (0.05) | 0.23 (0.04) | 0.22 (0.03) | Limb 0.67<br>Height 0.46<br>Int. 0.81 |
| | Prosthetic | 0.22 (0.04) | 0.22 (0.05) | 0.23 (0.05) | |
| Trail foot placement before the obstacle (m) | Preferred | 0.24 (0.05) | 0.25 (0.07) | 0.25 (0.07) | Limb 0.29<br>Height 0.15<br>Int. 0.60 |
| | Non-preferred | 0.23 (0.05) | 0.22 (0.04) | 0.24 (0.04) | |
| | Intact | 0.25 (0.06) | 0.26 (0.06) | 0.26 (0.06) | Limb 0.47<br>Height 0.15<br>Int. 0.19 |
| | Prosthetic | 0.22 (0.08) | 0.21 (0.06) | 0.21 (0.06) | |

**Table 2**
Group mean (SD) scalar error in target angle reproduction at the knee for intact versus prosthetic limbs and for preferred versus non-preferred limbs.

| Limb | Intact | Prosthetic | Preferred | Non-preferred |
|---|---|---|---|---|
| Absolute error (°) | 5.2 (3.6) | 4.5 (3.6) | 3.8 (3.2) | 5.8 (3.7) |
| *P* value | 0.34 | | 0.08 | |

suggests that efferent pathways are at least partially maintained following amputation. This could explain, in part, why laterality would be maintained following amputation but future research is required to confirm this. Furthermore, the joint receptors and muscle spindle receptors of and around the residual knee are largely unaffected by amputation; meaning sensory information regarding lower (prosthetic) limb movements are preserved. The above suggest that there may be too few 'drivers' to cause an alteration in an amputee's limb preference following amputation.

The differences in toe clearance but lack of differences in foot placements, together with the trend towards better knee joint-position sense for the preferred compared to non-preferred limb, suggest that laterality has an effect on swing limb motor control. We speculated that the differences observed between the preferred compared to non-preferred limb were related to a speed-accuracy trade-off, and hence that increases in foot clearance margins of safety would be accompanied by lower swing-limb foot velocities. Therefore, in order to better understand the interaction between speed and accuracy, we retrospectively determined lead foot forwards velocity at the instant of crossing; comparing between preferred and non-preferred limbs, as well as between intact and prosthetic limbs. Foot velocity at the instant of crossing was significantly ($p < 0.001$) lower for the preferred limb than the non-preferred limb (high obstacle; 3.03 $ms^{-1}$ preferred, 3.21 $ms^{-1}$ non-preferred, medium obstacle; 3.14 $ms^{-1}$ preferred, 3.27 $ms^{-1}$, non-preferred, low obstacle; 2.97 $ms^{-1}$ preferred, 3.31 $ms^{-1}$ non-preferred), but there were no differences when comparing between the intact and prosthetic limbs ($p = 0.46$). This suggests that, to some extent at least, laterality governs the trade-off between speed and accuracy, similar to that previously suggested to occur in able-bodied gait (Sparrow et al., 2008). It also suggests that there is better control of the lead-limb foot over the obstacle when crossing an obstacle leading with the preferred compared to non-preferred limb. Somewhat surprisingly, the only difference we found between leading with the prosthetic compared to intact limb was an increase in crossing speed when leading with the intact limb (Note there was no difference in crossing speed between the preferred and non-preferred lead-limb conditions). The higher crossing speed when leading with the intact limb may have been due to reduced comfort during stance on the prosthetic (trailing) limb resulting in participants wanting to rapidly transfer bodyweight back onto the intact (leading) limb. Alternatively, the lower crossing speed when leading with the prosthetic limb may have been due to the constraints related to how UTAs land on their prosthesis after crossing the obstacle (Buckley et al., 2013).

A limitation of this study was that lead-limb order was counterbalanced between intact and prosthetic limbs, and hence the order of preferred versus non-preferred limb was not counterbalanced. However, given that the preferred limb was the prosthetic limb in four of the nine participants, we don't believe the lack of 'counterbalancing' confounded the results presented. Another limitation was the self-report method we used to determine which limb was the preferred limb. We chose this pragmatic approach rather than use an experimental approach because use of an experimental approach would likely have been confounded by the mechanical constraints of the prosthesis. Future work should perhaps assess 'limb preference' in a more rigorous (experimental) manner. This could/should involve a cross disciplinary approach including neurophysiologists and psychologists. It would also be worthwhile investigating how participant characteristics such as cause of amputation, time since amputation, activity K-level, socket type and fit and so on may affect laterality.

## 5. Conclusion

These findings suggest that, despite the mechanical constraints imposed by use of a prosthetic device, laterality may be as important in lower-limb amputees as it has been shown to be (Sadeghi et al., 2000) in the able bodied. While the underlying mechanisms involved are unclear, they are certainly worthy of further investigation. Notwithstanding that, these preliminary results suggest that, during rehabilitative gait re-training, UTAs should be encouraged to step over obstacles leading with, whenever possible, whichever limb they feel most comfortable with because when they do margins of safety are increased and hence gait safety should be improved.

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