

Title: Obstacle crossing behaviour in transfemoral prosthesis users: The effect of prosthetic componentry

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ABSTRACT

Background

Functionally advanced prosthetic ankle-foot and knee components have separately been shown to positively affect obstacle crossing in individuals with a transfemoral amputation. It is unknown, however, what effect combining functionally advanced components has on transfemoral prosthesis users' obstacle-crossing strategies. The study aimed to assess how different knee and ankle-foot prosthetic components influence obstacle-crossing strategies in unilateral transfemoral prosthesis users.

Methods

Individuals with a unilateral transfemoral amputation (n=9) crossed an obstacle (30 cm x 10 cm x 8 cm) placed along an 8.3 m walkway. This was completed in four different prosthetic conditions: a combination of two different knee components (microprocessor and non-microprocessor) with one of two ankle-foot components (rigidly or hydraulically articulating ankles). Full-body kinematics were recorded as participants crossed the obstacles.

Findings

Obstacle-crossing strategies were not influenced by the prosthetic component combination. Although small changes were observed in kinematics (joint angles and centre of mass movement) and outcomes such as toe clearance and foot placement, these differences were not statistically significant.

Interpretation

When using different combinations of prosthetic ankle-foot and knee components, lower limb transfemoral prosthesis users make very small changes to movements during obstacle crossing. Obstacle-crossing strategies and outcomes are also not highly influenced by manipulating

component use, suggesting relatively high neuromotor flexibility in established unilateral transfemoral prosthesis users when crossing a small obstacle.

Introduction

Falling and the fear of falling can restrict people from participating in social activities, leading to reduced physical activity and placing burdens upon healthcare systems [1–3]. Annually, 33% of older adults fall, compared to over 50% of lower limb prosthesis users [3–5]. Over half of all community-dwelling lower limb prosthesis users report a fear of falling [3], which is linked with a higher risk of future falls [6].

Tripping over obstacles accounts for up to 53% [7] of all falls, and individuals with a transtibial amputation show increased failure rates when trying to avoid obstacles compared to healthy controls [7,8]. When crossing an obstacle is the desired outcome, the stance limb must establish a base of support to avoid a loss of balance [9], and the swing limb must avoid contact with the obstacle, thus avoiding subsequent trips [10]. To prevent contact with an obstacle, able-bodied ambulators adopt hip and knee flexion and ankle dorsiflexion in the swing limb [11–13]. Additionally, large movement in the mediolateral direction of the centre of mass can be attributed to instability and, therefore, a lack of balance [11]. For balance to be maintained, the centre of mass must be coordinated relative to the base of support [14], and different kinematic techniques can be adopted to preserve the relationship between the two adequately. Foot

placement control is an important outcome to provide stability [15], with foot placement dictating the base of support, directly impacting the mediolateral centre of mass location [16]. Prosthesis users negotiate obstacles more slowly and make contact with obstacles more frequently when under time pressure when compared to able-bodied individuals [17,18]. Individuals with transfemoral amputation typically exhibit reduced hip and knee flexion and decreased ankle dorsiflexion when crossing an obstacle, which may go some way to explaining the reduced success rate[17]. Transfemoral prosthesis users also frequently circumnavigate obstacles, showing increased hip circumduction and a more extended knee passing over the top of an obstacle[17]. These unsuccessful outcomes generally occur when crossing obstacles when the front of the foot contacts the front or top side of an obstacle on the floor[16]. Individuals with unilateral lower-limb amputation exhibit smaller minimum toe clearance when their crossing strategy is to lead with their prosthesis, compared to leading with their intact limb[19]. However, there is no apparent preference for either intact or affected limb lead limb selection strategies[20].

The prosthetic component may influence how safely a prosthesis user can cross an obstacle, with a knee joint and ankle joint making up a transfemoral limb. Hydraulically articulating ankle-foot components (HYD) typically incorporate passive articulation, meaning the foot remains dorsiflexed throughout swing when compared to less dorsiflexing articulating ankles, which incorporate the same foot device with a rigidly articulating ankle-foot component (RIG)[21–23]. Transfemoral prosthesis users require a prosthetic knee device in conjunction with an ankle-foot device to make up their prosthetic limb. More functionally advanced knees incorporate a microprocessor component (MPK), which increases stance control and includes a stumble recovery feature, locking the knee joint if the microprocessor component detects a trip or fall is imminent and provides more controlled flexion/extension of the joint. These

features have been shown to increase user confidence and reduce the number of falls when wearing a knee that is less functionally advanced[24,25].

As different knee and ankle-foot devices provide different movement mechanisms to the user, we explored which combination of four differing prosthetic componentry affected obstacle-crossing strategies. The current study aimed to investigate the effects of different ankle-foot and knee prosthetic componentry combinations on obstacle clearance adopted during the crossing stride in individuals with unilateral transfemoral amputation.

Methods

Participants

Individuals with a unilateral transfemoral amputation (IUTFs) (n=9, ♂ 9 were recruited according to the following inclusion criteria: age 18 and older, demonstrate a K3 level mobility level (able to negotiate stairs, ramps and walk continuously for 2 minutes), good (corrected) vision, no ongoing cardiovascular complaints. Exclusion criteria were musculoskeletal pain inhibiting self-selected walking speed, inability to complete tasks due to secondary illness (e.g. rheumatoid arthritis), being free from neuromuscular or musculoskeletal injury or falling regularly (>1 a month) as determined using the PROFANE fall definition [24] presence of discomfort or physical changes (e.g. blistering) in the residual limb. Participants provided written consent, and the study was approved by a national healthcare research ethics committee [REC reference 18/EM/0282].

Study Design

Individuals completed an obstacle crossing task in four prosthetic conditions, combining two knee components and two ankle-foot components. The knee component was either a mechanical, non-microprocessor component (MECH) or a microprocessor knee component

(MPK; Orion3, Blatchford Ltd, Basingstoke, UK). The ankle-foot components were either a non-articulating, rigidly attached component (RIG; Esprit, Blatchford Ltd, Basingstoke, UK) or a hydraulically articulating component (HYD; Echelon, Blatchford Ltd, Basingstoke, UK). All IUTFs had experience using all prosthetic components. The combinations were ordered via a random number generator, and the same experienced, licenced prosthetist changed all prosthetic components.

Study Protocol

Participants completed three obstacle (30 cm x 10 cm x 8 cm) clearances per condition, with the obstacle being placed 7.3 m along an 8.3 m walkway.

Movement Analysis

A 13-camera motion capture system (Qualisys, Gothenburg, Sweden) sampled kinematic data (100 Hz). Participants wore tight lycra shorts and performed the trials in their own flat-soled shoes. Reflective (64 x 14 mm) markers were attached bilaterally to the calcaneus, medial and lateral heel, the first, second and fifth metatarsal, medial and lateral malleoli and epicondyles, greater trochanter, iliac crest, posterior and anterior iliac spines. Tracking markers were attached to thigh and shank segments. Markers were attached medially and laterally on the axis of rotation on the prosthetic knee and where the articulation was present for the ankle-foot device. Trunk markers were placed on the xiphoid process, sternum, L5-S1, T8, and C7 spine. Left and right acromion, medial and lateral wrist, and elbow and a four-marker headband. The anterior part of the left and right feet was created digitally with a Digi pointer wand (C-Motion, Inc., Germantown, MD, USA).

Data Analysis

Marker trajectories were labelled and exported to Visual3D (C-motion, Germantown, MD, USA), where a low pass filter (zero-lag Butterworth, 10 Hz cut-off) was applied. Lead limb preferences were noted for each trial and reflected the self-selected crossing strategy of the

individual. To describe the technique of crossing the obstacle, the following measures were reported:

M-L range of motion; mediolateral whole-body centre of mass maximum minus minimum value of distances away from A-P CoM line achieved during the crossing stride. *Joint angles*: Transverse plane pelvis angle, frontal plane hip angle, sagittal plane hip, knee and ankle angles of lead and trail limbs. Kinematic variables were calculated during the crossing stride, defined as the final initial contact of the trail limb prior to crossing the obstacle to the initial contact of the trail limb after crossing the obstacle. Finally, the result of the selected crossing strategy and subsequent technique, the following outcomes were reported:

Initial foot placement: distance between the front side of the obstacle and the front of the trail foot leading into clearing the obstacle. *Final foot placement*: distance between the back side of the obstacle and the heel of the lead limb after clearing the obstacle. *Minimum toe clearance*: the vertical distance between the digitised front edge of the lead foot and the upper front edge of the obstacle as the foot crossed over the obstacle. *Crossing velocity*: anterior-posterior centre of mass crossing velocity during the crossing stride.

Statistical Analysis

Discrete variables of final foot placement, initial foot placement and vertical toe clearance were analysed using a two-way analysis of variance (knee*ankle) with crossing speed analysed using a two-way repeated analysis of variance. Where the assumption of sphericity was violated, a Greenhouse-Geisser correction factor was applied. Effect sizes (partial eta squared) were calculated for each statistical comparison, with the alpha level of significance set at $p=0.05$. All statistical analyses were conducted using the statistical package IBM SPSS software (v.26 IBM, Portsmouth, UK).

To analyse continuous variables (joint angles and M-L sway) across the crossing stride, Statistical Parametric Mapping (SPM) was used. This allows for the statistical comparison of complete trajectories instead of selecting specific features from those trajectories [26]. SPM involves the computation of a test statistic (e.g., ANOVA) at each time point, followed by applying random field theory to establish the significance threshold, all while maintaining a family-wise error rate of α . Consequently, instead of examining individual values, such as those at pre-defined times of a gait or stepping cycle, it becomes possible to analyse the entire biomechanical data trajectory while effectively managing multiple comparisons and the interdependence among adjacent time points. A custom version of Python (Python Software Foundation. (2023). Python version 3.12.2.) code based on the `spm1d` package was used [27]. For each participant, three trials for crossing the obstacle in the four experimental conditions were averaged before applying SPM. Ten Two-way ANOVAs were performed to test the significance of the prosthetic condition at each point in the crossing step (normalised from 0-100%) for the chosen variables. The time trajectory, $\text{SPM}\{F\}$, is the resulting F- statistic throughout the stepping cycle. The threshold for significance, α , was set at 0.05. In SPM packages, the clusters that cross the $\text{SPM}\{F\}$ threshold determine the p value of the cluster. When alpha is not crossed, non-significant p-values do not exist for cluster-level inference. Therefore, in the cases where alpha is not crossed, p-values are not reported per standard SPM practice for reporting cluster-level probabilities

Results

Lead limb preference

There was no common lead limb preference strategy across participants, regardless of the prosthetic componentry combination used. A total of 4/8 participants remained consistent in

their choice of lead limb across all trials, with 2 participants leading with their intact limb across all trials and 2 with their prosthetic limb across all trials (Table 1). The other four participants showed variety in their lead limb selection. The MPK+HYD condition saw the highest percentage/proportion of participants leading the crossing stride with their intact limb at 58.53%. All other conditions saw participants prefer crossing leading with their prosthetic limb.

Table 1. Participants lead limb preference (%) mean per condition across all trials.

Lead Limb Preference	MECH+ HYD	MECH+ HYD	MECH+ RIG	MECH+ RIG	MPK+ HYD	MPK+ HYD	MPK+ RIG	MPK+ RIG	All conditions	
	Pros	Intact	Pros	Intact	Pros	Intact	Pros	Intact	Pros	Intact
UTF1	100	0	33	66	66	33	100	0	75	25
UTF2	0	100	0	100	0	100	0	100	0	100
UTF3	100	0	100	0	100	0	100	0	100	0
UTF4	66	33	100	0	0	100	66	33	58.33	41.67
UTF5	0	100	0	100	0	100	0	100	0	100
UTF6	100	0	100	0	66	33	100	0	91.67	8.33
UTF7	0	100	0	100	0	100	33	66	8.33	91.67
UTF8	100	0	100	0	100	0	100	0	100	0
Mean	58.53	41.67	54.17	45.83	41.67	58.53	62.5	37.5	54.16	45.83

Waveform analysis of kinematics

Visual inspection of time series data shows little differences in crossing stride kinematics in the four experimental conditions. Statistical Parametric Mapping revealed no statistically significant differences in all observed waveforms across the crossing stride of the four prosthetic combinations (Figure 1). Maximum F-value (F_Max) for the effect of the knee, ankle and interaction effect of the knee and ankle components are reported.

Visual inspection of Figure 1 shows that MECH and MPK conditions deviated in pelvic rotation (increased rotation during mid-cross stride when using MPK) (F_Max = 1.4 (knee), 1.3 (ankle) and 2.8 (knee*ankle interaction)), lead limb hip abduction (increased during the first half of crossing stride using MPK) (F_Max = 3.0 (knee), 0.5 (ankle) and 2.0 (knee*ankle

interaction), and lead limb ankle plantarflexion (increased plantar flexion in MPK throughout crossing stride) ($F_{\text{Max}} = 10.6$ (knee), 1.9 (ankle) and 2.8 (knee*ankle interaction)). However, as stated, these deviations were not statistically significant.

All other observed variable waveforms showed little to no differences between prosthetic combinations: mediolateral centre of mass ($F_{\text{Max}} = 0.6$ (knee), 0.3 (ankle), and 0.1 (knee*ankle interaction)), trail limb hip abduction ($F_{\text{Max}} = 1.7$ (knee), 4.5 (ankle) and 1.3 (knee*ankle interaction)), lead and trail hip flexion ($F_{\text{Max}} = 2.3$ & 1.6 (knee), 5.9 & 3.5 (ankle) and 5.3 & 3.5 (knee*ankle interaction)) and knee flexion ($F_{\text{Max}} = 1.6$ & 0.4 (knee), 0.9 & 1.0 (ankle) and 1.2 & 0.9 (knee*ankle interaction)), and trail ankle dorsiflexion ($F_{\text{Max}} = 1.6$ (knee), 1.4 (ankle) and 0.5 (knee*ankle interaction)).

Final foot placement

No statistically significant differences were found for lead limb final foot placement (Figure 2) MECH+HYD (0.30 m), MECH+RIG (0.18 m), MPK+HYD (0.38 m), and MPK+RIG (0.37 m), for main effects of knee ($F(1,28) = 2.39$, $p=0.13$, $\eta_p^2 = 0.08$), ankle ($F(1,28) = 0.46$, $p=0.50$, $\eta_p^2 = 0.02$) or knee*ankle interaction ($F(1,28) = 0.44$, $p=0.51$, $\eta_p^2 = 0.02$). Trail limb final foot placement also showed no significant differences (MECH+HYD 0.72 m, MECH+RIG 0.76 m, MPK+HYD 0.51 m, MPK+RIG 0.71 m) for main effects of knee ($F(1,28) = 2.10$, $p=0.16$, $\eta_p^2 = 0.07$), ankle ($F(1,28) = 1.79$, $p=0.19$, $\eta_p^2 = 0.06$) or knee*ankle interaction ($F(1,28) = 0.66$, $p=0.42$, $\eta_p^2 = 0.02$).

Initial foot placement

Lead limb initial foot placement exhibited no significant differences across conditions (Figure 2) MECH+HYD (-1.1 m), lead MECH+RIG (-1.01 m), lead MPK+HYD (-1.21 m), and lead MPK+RIG (-0.96 m), for main effects of knee ($F(1,28) = 0.10$, $p=0.75$, $\eta_p^2 < 0.01$), ankle ($F(1,28) = 3.59$, $p=0.07$, $\eta_p^2 = 0.11$) or knee*ankle interaction ($F(1,28) = 0.77$, $p=0.39$, $\eta_p^2 =$

0.03). Neither did trail limb final foot placement: MECH+HYD (-0.62 m), trail MECH+RIG (-0.62 m), trail MPK+HYD (-0.55 m), and trail MPK+RIG (-0.43 m), for main effects of knee ($F(1,28) = 2.33$, $p=0.14$, $\eta_p^2 = 0.08$), ankle ($F(1,28) = 0.39$, $p=0.54$, $\eta_p^2 = 0.01$) or knee*ankle interaction ($F(1,28) = 0.53$, $p=0.47$, $\eta_p^2 = 0.02$).

Minimum toe clearance

No significant differences were found in minimum toe clearance for both lead and trail limbs (Figure 2). Lead MECH+HYD (0.12 m), lead MECH+RIG (0.13 m), lead MPK+HYD (0.13 m), lead MPK+RIG (0.12 m), ($F(3,18) = 0.60$, $p=0.62$, $\eta_p^2 = 0.09$) c). Trail MECH+HYD (0.11 m), trail MECH+RIG (0.09 m), trail MPK+HYD (0.09 m), trail MPK+RIG (0.13 m) with no significant main effects of knee ($F(1,28) = 0.59$, $p=0.45$, $\eta_p^2 = 0.02$), ankle ($F(1,28) = 0.21$, $p=0.65$, $\eta_p^2 < 0.01$) or knee*ankle interaction ($F(1,28) = 3.41$, $p=0.08$, $\eta_p^2 = 0.11$)).

Crossing velocity

Crossing velocity also displayed no significance (Figure 2): MECH+HYD (0.82 m/s), MECH+RIG (0.85 m/s), MPK+HYD (0.89 m/s), and MPK+RIG (0.83 m/s), ($F(3,21) = 0.85$, $p=0.48$, $\eta_p^2 = 0.11$).

Consistent lead limb strategy observation

Waveform comparisons of participants who selected the same lead limb to cross with for all trials in all prosthetic conditions were compared observationally with no statistical analysis performed. Participants three and eight (Figure 3) selected their prosthetic limb to lead in every trial, and participants two and five (Figure 4) chose their intact limb. Visual inspection of the time series data indicates ankle dorsiflexion during the crossing stride was greater when using the MECH knee condition when leading with the prosthetic limb, alongside greater pelvic rotation and hip adduction using the MPK. Differences between conditions appeared minimal

when visually inspecting the waveforms of time series data of users who led consistently with their intact limb.

Discussion

The aim of this study was to investigate the effects of different prosthetic knee and ankle-foot combinations during obstacle crossing in people with unilateral transfemoral amputation. All participants successfully performed obstacle crossing in all prosthetic combinations. However, despite some small changes in variables, there was no apparent effect on lead limb preferences, foot placement, lower kinematics and centre of mass dynamics. This may reflect a relatively high level of neuromotor flexibility in the current sample of unilateral transfemoral prosthesis users when crossing a small obstacle. The observed consistency of strategies, movement and outcomes when using a wide variety of combinations of prosthetic componentry suggests that these individuals could adapt to these conditions to maintain a stable obstacle crossing behaviour.

Results from the waveform analysis whereby participants were both grouped together (figure 1) and where participants lead exclusively with their prosthetic limb (figure 3) show that the type of knee component used visually showcases two different ankle dorsiflexion strategies when crossing the obstacle, with mechanical, non-microprocessor knees eliciting larger amounts of ankle dorsiflexion during the crossing step, although this was not statistically significant. Increased ankle dorsiflexion is associated with obstacle avoidance [11–13], indicating the mechanical non microprocessor knee may offer a strategy to increase vertical toe clearance via increasing ankle dorsiflexion. The microprocessor knee and hydraulic ankle combination, however, provided the largest vertical toe clearance in the absence of increased dorsiflexion, meaning that the increased vertical toe clearance in the MPK condition comes from an alternative obstacle-crossing strategy. When using the MPK, participants exhibited a greater amount of pelvic rotation, suggesting that with this combination, they were more likely

to circumduct the obstacle. Circumduction is often coupled with a more extended knee and greater hip abduction [17], thus enabling individuals to increase the height in which their toe can avoid an obstacle. The goal of obstacle crossing is to successfully clear the obstacle without making contact or losing balance [9], avoiding a trip or a fall altogether [10]. Increased mediolateral centre of mass sway can be an indication of whether one strategy (increased dorsiflexion versus increased pelvic rotation) provides a safer way of crossing [10,11]. However, results from the present study suggest minimal deviations in the mediolateral centre of mass, suggesting that participants displayed a strong maintenance of balance throughout the crossing stride in all combinations of components.

Participants in the current study had free choice of which limb to lead with when crossing the obstacle. Half of the participants showed no preference in which limb they crossed the obstacle with (Table 1). In contrast, half of the participants remained consistent in their choice, either crossing consistently by leading with their intact (Figure 4) or by leading with their prosthetic limb (Figure 3). This outcome shows that there was no apparent preferred limb to use as a base of support when leading, nor one to use as a landing limb, suggesting prosthetic componentry did not strongly influence crossing behaviour when choosing which limb to lead with. Participants, however, crossed more quickly and started their crossing stride from further back when using the most advanced combination (Figure 2), which may indicate an increase in confidence with the more advanced ankle and knee combinations. However, this was not supported by statistically significant effects in the relevant variables, so this explanation is made with caution.

There are several limitations from the current work that should be considered. The study had a small sample size consisting of males only, likely affecting the subsequent statistical power,

the likelihood of detecting significant differences between selected parameters, and the generalisability of findings. Additionally Participants were given the choice of which limb they led the crossing of the obstacle with. Whilst this allowed for exploration of their chosen obstacle-crossing strategies, it unavoidably created sub-divisions of obstacle-crossing strategies that may also have affected statistical power. However, as the study was interested in participants' volitional behaviours during the crossing stride when provided with different components, it was beyond the scope to collect additional trials enforcing a crossing strategy. Future works may compare the two lead limb crossing strategies, as well as exploring measures of joint moments and powers, alongside considering whole body kinematics to describe crossing behaviour more completely.

Conclusion

When using different combinations of prosthetic knee and ankle-foot components, individuals with unilateral transfemoral amputation were able to cross a small floor-based obstacle during gait safely. However, each prosthetic component combination had no clear effect on lead limb preferences, thereby making an informed outcome on joint kinematics difficult. However, foot placement, centre of mass dynamic and toe clearance, combined with a one hundred percent success rate when crossing the obstacle across all combinations suggests that for mobile and active individuals with a unilateral transfemoral amputation, prosthetic component selection could focus more greatly on obstacle-crossing safety features in other aspects of the individual lifestyle, such as walking or stair negotiation, without fear of a negative impact on obstacle crossing.

Declarations of interest: none.

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