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Title: Joint moments during downhill and uphill walking of a transfemoral amputee with a hydraulic articulating and a rigid prosthetic ankle – a case study

Short title: Joint moments during sloped walking of a transfemoral amputee

Abstract

Introduction: Functional characteristics of prosthetic ankle design may facilitate sloped walking for transfemoral amputees. The aim of the current case-study was to analyse the effects of a rigid vs. a hydraulically articulating ankle component on the biological joint moments of a transfemoral amputee during downhill, uphill and level walking.

Methods: The gait of one unilateral transfemoral amputee, using the same prosthetic foot with rigid and hydraulic ankle components, was analysed and compared to a control group of 18 able-bodied participants. Kinematic and kinetic data were recorded at self-selected walking speed on a sloped ramp with inclinations of -12°, -4° (downhill), 0° (level), +4° and +12° (uphill).

Results: The slope influenced lower limb joint moments similarly in both able-bodied and transfemoral participants. The effect of altering ankle movement through exchanging prosthetic ankle componentry was most acutely seen at the hip joint of the residual limb. The use of a hydraulic ankle joint component resulted in decreased mean hip joint extension and flexion moments of up to 92% and 48% respectively in the residual limb when compared to using the rigid ankle joint component, respectively.

Conclusion: During sloped walking, the use of a hydraulically articulating vs. rigid ankle joint component reduced the joint moments observed at the hip joint of the residual limb in a unilateral transfemoral amputee. This indicates a benefit for transfemoral amputees as the increased ankle function reduces the moment producing requirements of the hip joint which may result in decreased energy consumption and subsequently, a more efficient gait.

Keywords

Amputation, prosthetics, slope, gait, incline

Introduction

For lower limb amputees, sloped walking is a more complex neuromotor task when compared to level walking due to the mechanical characteristics and constraints of prosthetic componentry that necessitate the adoption of compensatory gait mechanisms.[1, 2] The lack of ankle mobility, which aids toe-clearance during swing, a controlled placement of the foot during stance and an active push-off, is compensated for by different biomechanical[3, 4] strategies in both the residual and intact limbs, leading to an asymmetric gait pattern.[3, 5-7] Previous research has shown that a hydraulic ankle articulation is beneficial when compared to a rigid ankle during level gait for both transtibial (TT) and transfemoral (TF) amputees.[8-11] These studies reported that when using a hydraulic vs. rigid ankle component, forward progression of the centre of pressure and minimum toe clearance increased and total work done by the intact limb is reduced, resulting in an increased freely chosen walking speed.[8, 11] Therefore, ankle joints providing hydraulic articulation between prosthetic shank and foot during stance, may overcome these issues and be more beneficial when compared to a rigid ankle mechanism during both level and slope walking.[8-11]

During slope walking in able-bodied participants, increased joint moments have been reported, potentially increasing the risk of potential overuse injury.[12] This is relevant to lower limb amputee slope walking as a correlation between joint moments and osteoarthritis was suggested in the able-bodied population,[13] and osteoarthritis is a common secondary comorbidity for lower limb amputees.[14, 15] However, in lower limb amputees the effect of sloped walking on joint moments has not been widely reported.[1, 16-18] To the authors' knowledge, little information exists on the effect of sloped walking on joint moments and specifically, what effect an hydraulically articulating ankle joint has when compared to a rigid ankle joint.[3] The existing research on sloped walking shows for TT amputees that the use of different kinds of ankle articulations, can reduce joint moments (Proprio Foot®, Össur, adjusting "neutral" position to the slope gradient during swing)[3] and internal stresses in the residual limb (Echelon, Chas A Blatchford & Sons Ltd, hydraulic control (-3° - +6°) during stance, toe-up for swing through clearance).[9]

However, results obtained from TT amputee gait cannot necessarily be applied to TF amputee gait, as TF amputees cannot actively flex their prosthetic knee. During stance the knee joint is in a stable position, while during swing it flexes passively to swing the residual limb forward. As such, TF amputees show an increased hip peak flexion moment in prosthetic limb terminal stance, as the hip flexors need an increased activity to push off the prosthetic limb and initiate knee flexion.[4] Additionally, to allow for sufficient toe clearance during swing, some TF amputees use vaulting (propulsive plantarflexion of the intact limb during intact limb push-off) as a gait compensatory mechanism.[19] This could possibly lead to observed differences of joint moments between TT, TF and control participants during level walking.[20] During uphill walking the inclined surface complicates the swing through of the prosthetic limb (toe clearance), and the lift of the CoM over the body against gravity requires higher positive net work,[21] while for downhill walking the lowering of the CoM during stance requires negative net work.[21] Consequently, uphill and downhill walking differ considerably: during uphill walking the ankle needs to adapt while during downhill walking the knee needs to adapt.[22] If TF amputees are able to reduce the braking effect also during downhill and uphill walking, and can transfer their bodyweight more quickly over the prosthetic foot, this would result in a decreased hip flexion and further in a decreased hip joint moment. During downhill walking the braking resistance of the hydraulically articulating ankle joint could additionally enable a controlled support for the forward and downward movement of the body. However, to the authors' knowledge, no information is available on the effect of different prosthetic ankle components on joint moments in TF amputees during sloped walking.

Thus, the aim of this case study was to analyse the effects of a hydraulically articulating ankle joint component compared to a rigid ankle joint component on joint moments for a unilateral transfemoral amputee during level walking and a variety of downhill and uphill inclinations.

Methods

One male unilateral transfemoral amputee (age: 44 years, height: 1.84 m, mass: 85 kg, traumatic aetiology 29 years previous) was recruited, informed consent was provided and the study was approved by the University's ethics board. The participant used a Milwaukee TF socket (Guenther Bionics GmbH, Germany) and a prosthetic knee joint (Model: Orion, Chas A Blatchford & Sons Ltd, UK), which consists of a combination of a hydraulic and a pneumatic unit.[23] A comparison of the following prosthetic ankle components was performed: (1) A hydraulically articulating ankle component (ARTIC) (Model: Elan, Chas A Blatchford & Sons Ltd, UK): Hydraulic ankle joint with adaptive resistance during dorsi-flexion and plantar-flexion (-3° to 6°). The ankle joint is equipped with a microprocessor controlled speed and terrain response. During descending, a braking mechanism and during ascending, an energy return mechanism are supposed to support the gait, (2) a rigid ankle component (RIGID) (Model: Esprit, Chas A Blatchford & Sons Ltd, UK): RIGID ankle joint. For ARTIC and RIGID, the same foot consisting of an e-carbon heel and toe spring was used. This foot allows for plantar and dorsiflexion (heel & toe spring) as well as for pronation and supination (two-toed leaf spring design). The participant was familiarized with both ankle joints by using them alternately several months prior to testing. During the study approximately one hour was given to adapt to each ankle component.

An instrumented ramp (6 m x 1.5 m) with two force plates (AMTI, Advanced Mechanical Technology Inc., Watertown, Massachusetts, USA, 600x1200 cm) imbedded in the middle of the walkway was set consecutively to the slopes of -12°, -4° (downhill), 0° (level), +4° and +12° (uphill) (Figure 1). The ramp was tilted to each inclination (controlled by a digital goniometer) around the pivot point in the middle of the ramp using an electrichydraulic device.[24] A correction of orientation with respect to the reference coordinate system was performed by using the force plates' corner positions for each inclination. The force plate data were sampled at 1000 Hz. Kinematic data were recorded with a twelve-camera motion capture system (Vicon, Oxford Metrics Ltd, Oxford, UK) at 250 Hz sampling frequency. Reflective markers were placed on the lower extremities according to the Cleveland Clinic Marker set (Motion Analysis Corp., Santa Rosa, CA, USA), which uses an anatomical landmark calibration technique. Markers to identify the calibration landmarks on the prosthetic knee were placed medially and laterally of the rotational joint centre of the prosthetic leg. At the prosthetic ankle the calibration landmark were placed medially and laterally of the spring-loaded axle, while the respective foot segment markers were chosen to correspond to those on the intact side. For each slope, five trials at self-selected walking speed were recorded. Kinematic and kinetic data were filtered using a Butterworth filter with 6 Hz cut-off frequency. Mean values of the five trials were calculated for all parameters and used as representative values.

To compare the unilateral TF amputee with able bodied persons, data from an existing male control group (n=18, age: 27 ± 5 years, height: 1.80 ± 0.05 m, mass: 75 ± 8 kg) were used. Since no data for 4° were available, the comparison was limited to level walking and 12° uphill and downhill walking. For each participant and each slope, one representative trial was used (median walking speed).

Spatio-temporal parameters (speed, stance time and single support time), ground reaction forces (GRFs), sagittal joint angles and sagittal joint moments were calculated using a six degree of freedom model within Visual 3D (C-Motion Inc., Germantown, USA).[25] Joint angles, GRFs and net joint moments were time-normalized over stance phase and normalized to body mass. Ankle, knee and hip joint moments of the intact limb and the hip joint moments of the residual limb were calculated, since only intact biological joints were considered. Joint moments are shown as internal extension (i.e. positive moment values) and flexion (i.e.

negative moment values) moments throughout. For the TF amputee therefore for each inclination, joint and type of prosthesis average curves over the 5 trials were calculated and graphically visualized. Furthermore, the able-bodied group, group mean values of their representative trials along the stance phase pathway were calculated and graphically visualized as average curves. The mean extension (average over all positive values) and the mean flexion moment (average over all negative values) were calculated for each inclination, joint and prosthetic ankle component, as it was previously done in a similar setting for muscle forces.[26] Values are presented as mean over the 5 trials (TF amputee) and as mean over the entire group (control group) along with the 95% confidence interval (95% CI).

Results

SPATIO-TEMPORAL PARAMETERS

The spatiotemporal parameter (speed, stride frequency, stride length, step length, stance time and single support time) for the TF amputee using ARTIC and RIGID during downhill, level and uphill walking are shown in Table 1.

JOINT MOMENTS

Figure 2 presents the joint moments over the entire stance phase of all intact biological lower limb joints for TF amputee using both ankle joint components as well as for the control group. Independent of the ankle component, downhill walking led to increased intact knee extension moments, while uphill walking mainly increased hip and ankle joint moments compared to level walking. For the residual hip joint, the joint moment curves of ARTIC, RIGID and control group differed substantially from each other in terms of profile, direction of moment (extension/flexion) and time of maximum and minimum values (Figure 2).

Over all inclinations, mean extension moments were similar or decreased in all joints using ARTIC. Mean flexion moments were similar or decreased in both hip joints except for the -12° condition and similar or slightly increased in the ankle and knee joint, respectively (Figure 3).

Intact ankle: Mean extension moments at the intact ankle decreased by 1-8% when using ARTIC compared to RIGID (Figure 3). Mean intact ankle flexion moments were about 28% increased for -12° downhill walking, and 12-17% decreased during ±4° inclines and level walking when using ARTIC compared to RIGID.

Intact knee: In the intact knee joint, mean knee extension moments were, over all inclinations, 17-29% lower when using ARTIC compared to RIGID, while mean knee flexion moments were higher.

Intact hip: At the intact hip joint, similar mean extension moments were found for ARTIC compared to RIGID. Mean intact hip flexion moments were between 4-19% lower for ARTIC, except at 12° uphill walking when mean hip flexion moments were 27% higher for ARTIC in comparison to RIGID.

Residual hip: At the residual hip joint, mean extension and flexion moments were lower using ARTIC compared to RIGID. Residual hip joint moments were found to be 50-92% (extension) and 17-48% (flexion, except -12°) lower, using ARTIC compared to RIGID (Figure 3). Since the greatest differences between control group joint moments as well as between different ankle joint components occurred in the hip joint of the residual leg, we focus on these below.

GROUND REACTION FORCES AND JOINT ANGLES

Downhill

Vertical GRF as well as ankle, knee and hip joint angles of the residual side during -12° downhill walking are shown in Figure 4. The peak vertical GRF during weight acceptance was highest in the control group, followed by the ARTIC and lowest with the RIGID component. The peak vertical GRF during push off (terminal stance) was highest for RIGID, while the ARTIC showed similar peak values to the control group. The knee angle shows that the participant used the yielding function (flexion during stance) of the prosthetic knee in the -12° gradient, which he did not use at -4°. During -12° downhill walking the amputee’s hip joint angle differed considerably from the control group. Although higher GRFs at weight acceptance occurred when using ARTIC compared to RIGID (Figure 4), the hip joint extension moments during -12° downhill walking were lower using ARTIC (Figure 2).

Uphill

In contrast to the control group, the TF amputee did not show distinct weight acceptance and push off peaks in the vertical GRF curves for the residual side (Figure 5). The differences between ARTIC and RIGID were, however, minor. Differences between the two ankle components were greater for the joint angles compared to the vertical GRF.

Discussion

The aim of the current study was to analyse the effects of a hydraulically articulating ankle joint compared to a rigid ankle joint on joint moments for a unilateral TF amputee during level and sloped walking. The effect of a hydraulically articulating ankle were most pronounced at the residual limb hip joint, leading to decreased joint extension (up to 92%) and flexion (up to 48%) moments compared to the rigid component.

The faster walking speed during level walking (9%, Table 1) when using a hydraulic ankle component observed in the current study is in agreement with de Asha et al.,[8] who also showed a faster self-selected walking speed in TF amputees with a similar prosthesis. The tendency for longer single support time of the intact limb throughout all inclinations when using ARTIC compared to RIGID (Table 1) may be explained by increased toe clearance[27] and an improved swing phase of the residual limb when using the hydraulic ankle component.

The effect of sloped walking on joint moments is similar to that of able-bodied participants. During downhill walking, joint moments at the knee were increased with increasing inclination, while during uphill walking, the hip extension moment, and to a lesser extend the ankle and knee joint extension moments, increased with increasing slope, in order to elevate the CoM.[28]

This case study showed that the use of hydraulic ankle joint can reduce the joint moments during downhill and uphill walking. This corroborates previous studies showing reduced joint moments[3, 29] and internal stresses in the residual limb[9] using different concepts of articulating ankle joints. Portnoy et al.[9] found a 300% lower loading rate of the residual limb while using a hydraulic foot compared to an energy storage and return prosthetic foot in TT amputees when walking on sloped and irregular surfaces. Fradet et al.[3] showed the potential to reduce joint moments of TT amputees during sloped walking by using an in swing phase adaptive ankle foot system compared to an ankle joint prosthesis in neutral position. The authors report for uphill walking a bilateral reduction of internal knee flexion moment and internal plantarflexion moment during stance as well as a decreased residual limb internal knee extension moment at the contralateral foot-off during downhill walking.[3]

In the current study joint moments were also reduced when using the hydraulic compared to the rigid ankle component. During -12° downhill walking the TF amputee used the yielding function of the prosthetic knee with both ankle devices (knee angle Figure 4), however, this function was not used at -4°. In order to activate the yielding function the CoM needs to be posterior of the knee joint centre of rotation and hence the hip angle remains flexed throughout stance. With the hydraulic ankle component the hip flexion angle was decreased compared to with the rigid ankle, which further explains to the up to 92% decreased hip extension moment (Figure 6).

The decreased hip joint extension moment (up to 78%) of the residual limb during uphill walking when using ARTIC compared to RIGID can be explained by the same mechanism. The participant's posture during prosthetic initial double support (including a more extended hip joint angle) enabled a reduced lever arm between the GRF and the hip joint centre, explaining the observed joint moment reduction when using the articulating compared to rigid ankle component.

De Asha et al.[8, 11] identified benefits of a similar hydraulic ankle joint during early prosthetic stance during level walking. Using the hydraulically articulating ankle, TT and TF amputees were able to transfer the bodyweight onto the prosthetic limb more smoothly, which allowed for a quicker translation of the CoM over the foot.[8, 11] Although not quantified in the current study, during both downhill and uphill walking, it is possible that the CoM position over the prosthetic limb at weight acceptance (downhill: Figure 6) was improved when using ARTIC compared to RIGID. This might be due to the mechanisms described by De Asha et al. during level walking,[8, 11] consequently leading to reduced hip joint extension moments (Figure 2 & 3) using the hydraulic ankle component.

Furthermore, in the current study also the mean hip flexion moments of the residual limb were reduced by up to 48% when using the hydraulically articulating compared to the rigid ankle component. Differences between ARTIC and RIGID were most dominant during level (-48%), -4° downhill (-37%) and +4° uphill (-34%) walking (Figure 2 & 3). Bonnet et al.[4] observed for TF amputees an increase in the hip flexion moment during the prosthetic limb terminal stance phase, which is necessary for initiating prosthetic knee flexion. In agreement with Bonnet et al.,[4] maximum hip flexion moments at the residual limb were higher than those at the intact limb as well as higher than controls. This is true for all sloped walking conditions except -12° downhill walking, were due to the yielding mechanism hardly any flexion moment was generated by the TF amputee in the current study (Figure 2 & 3). Schmalz et al.[30] suggested that the increased hip flexion moment required to initiate knee flexion in late stance phase is created by muscular effort, which is the likely cause for their observed increase in oxygen consumption. Thus, a decreased hip flexion moment when using ARTIC compared to RIGID could possibly lead to a reduction in oxygen consumption, at least during level walking and lower inclinations.

Finally, most studies showed that people with lower-limb amputation often load their intact lower limb more during daily activities, which can lead to degenerative changes such as osteoarthritis of the knee and/or hip joints of the intact limb.[15] Kulkarni et al.[31], however, examined 44 lower limb amputees and found that 55% of the residual hips and 18% on the intact side were positive for osteoarthritis. Furthermore, TF amputees developed significantly more frequent hip osteoarthritis in the residual side than TT amputees.[31] This suggests that the use of the hydraulically articulating compared to the rigid ankle component and subsequent reduction in hip moments may also be relevant for the prevention of osteoarthritis in TF amputees.

These findings of the current study apply to an individual active TF amputee and generalization to a wider population must be made with caution. The recruitment of several TF amputees, who are all fully adapted to the different prostheses over a long period of time, however, is practically difficult to achieve. Therefore, while acknowledging the limitations, this case study provided useful comparisons without major influences of patient adaptation on the data. It remains unclear, however, to what extent ankle movement is induced by the hydraulic unit and what amount is induced by the deformation of the carbon fibre components. Although not the specific focus of the current study, it must be acknowledged that settings of the knee unit may also influence the responsiveness of the rigid or articulating ankle and warrants further investigation.

Conclusion

Using a hydraulically articulating ankle component led to small alterations in spatio-temporal parameters and partly substantial alterations on joint moment level when compared to a rigid ankle component. The differences resulting from the use of a hydraulically articulating ankle were most pronounced at the residual limb hip joint, where the use of the articulating ankle component decreased joint extension (up to 92%) and flexion (up to 48%) moments compared to the rigid component. The reduction of residual limb hip joint extension moments when using the hydraulic compared to the rigid ankle was caused by an altered CoM position over the prosthetic limb during initial prosthetic double support. Decreased residual limb hip flexion moments during terminal prosthetic double support when using the hydraulically articulating compared to the rigid ankle component could possibly lead to a reduction in energetic cost. Finally, reduction in hip moments may also be relevant for the prevention of osteoarthritis in TF amputees.

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Figures

Figure 1: Measurement set up during downhill walking of the transfemoral amputee.

Figure 2: Ankle, knee (intact limb only) and hip (both limbs) joint moments using the hydraulically articulating (ARTIC) and rigid (RIGID) ankle components and for controls.

Figure 3: Mean extension and flexion moments for the ankle, knee (intact limb only) and hip (both limbs) over stance phase. Error bars represent the 95% confidence interval.

Figure 4: Vertical ground reaction force (GRF), ankle, knee and hip joint angle of the residual leg at 12° uphill walking.

Figure 5: Vertical ground reaction force (GRF), ankle, knee and hip joint angle of the residual leg at -12° downhill walking.

Figure 6: Schematic comparison between the hydraulically articulating (ARTIC) and rigid (RIGID) ankle components at weight acceptance.