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Gait initiation in lower limb amputees

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Abstract

Objective: To study limitations in function and adjustment strategies in lower limb amputees during gait initiation.
Design: Observational cohort study.
Setting: University Medical Center.
Participants: Amputees with a unilateral transfemoral or transtibial amputation, and able-bodied subjects.
Main outcome measures: Leading limb preference, temporal variables, ground reaction forces, and centre of pressure shift.
Results: Amputees demonstrated a decrease in peak anterior ground reaction force, a smaller or absent posterior centre of pressure shift, and a lower gait initiation velocity. The main adjustments strategies in amputees were more limb-loading on the non-affected limb, prolonging the period of propulsive force production in the non-affected limb and initiating gait preferably with the prosthetic limb.
Conclusion: Since an intact ankle joint and musculature is of major importance in gait initiation, functional limitations and adjustment strategies in transfemoral and transtibial amputees were similar. Improving prosthetic ankle properties and initiating gait with the prosthetic limb may facilitate the gait initiation process in amputees.
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Keywords: Gait; Balance; Amputation; Prosthetics; Rehabilitation

Most studies concerning human gait have focused on steady-state walking. However, for safe independent locomotion other aspects of gait are important as well. The transition from standing to walking is a task which is often required in daily life and challenges balance control. [1,2] Compared to steady-state walking, the requirements on the neuromuscular system are increased in gait initiation, since a complex integration of neural mechanisms, muscle activity and biomechanical forces is necessary [1].

Postural adjustments and muscle activity at the ankle and hip are needed to initiate gait. The limb that moves forward first is called the leading limb and the other limb is termed the trailing one. Able-bodied individuals activate tibialis anterior muscle and inhibit soleus activity to shift the centre of pressure (COP) posteriorly and to accelerate the centre of mass (COM) anteriorly [3–9]. As a result, the ground reaction force (GRF) in the anterior direction increases, thereby generating a forward momentum [3,10]. Simultaneously, abductor muscles in the leading limb shift the COP toward this limb [3,11]. Prior to heel-rise of the leading limb the COM is shifted toward the trailing limb, which unloads the leading limb and creates a stable base for balance control in single-limb stance [12]. Finally, a burst of soleus muscle activity initiates push-off of the leading limb [7,8], whereas the COM is accelerated further in a forward and medial direction [13].

The amputated limb is affected by sensory loss, while muscles and joint(s) are absent. Gait initiation requires two skills that may be limited in amputees, propulsion and balance control. Previous studies in amputees have shown inconclusive results concerning COP trajectory, which is an

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important outcome measure in gait initiation [1,8,14]. In only two studies transfemoral amputees were tested next to transtibial amputees [8,15], and one study included an able-bodied control group [14]. Moreover, in all studies gait was initiated in response to a starting signal [1,8,14,15].

The first goal of this study was to determine limitations in function in the prosthetic limb of transfemoral and transtibial amputees during self-initiated gait. We hypothesized that posterior COP shift and anterior GRF in the prosthetic limb will be reduced which results in a lower gait initiation velocity in amputees. The second purpose of this study was to identify adjustment strategies used by amputees to compensate for the limitations in function. To enhance propulsion, amputees will produce a larger and prolonged anterior GRF in the non-affected limb. To ease balance control amputees will increase limb-loading on the non-affected limb and shorten single-limb stance duration on the prosthetic limb. Finally, amputees will prefer to initiate gait with the prosthetic limb which serves both propulsion and balance.

1. Methods

1.1. Subjects

Subjects with a unilateral transfemoral (TF) or transtibial (TT) amputation were recruited from a prosthetics workshop. Inclusion criteria included an amputation for at least 1 year, daily use of a prosthesis and the ability to walk more than 50 m without walking aids. A control group of able-bodied subjects (AB) was also selected. They were recruited via advertisements at the local blood bank, hospital, television and radio station. Subjects were excluded if they had any medical conditions that could affect their mobility or balance, such as neurological, orthopaedic or rheumatic disorders, cognitive problems, severely impaired vision, or sensory loss at the non-affected limb(s). Furthermore, amputees with pain or wounds at the amputation limb or prosthetic fitting problems were excluded.

The study group consisted of 7 TF, 12 TT and 10 AB. The medical ethics committee approved the study protocol. All subjects provided informed consent before testing. Amputees used different prosthetic feet and all TF used free moveable prosthetic knees. Subject characteristics are shown in Table 1.

1.2. Apparatus

The study was performed in a motion analysis laboratory, which is equipped with an 8 m long aluminium walkway and a force plate[1] of 40 cm × 60 cm. We recorded the gait initiation process with video cameras. The sampling frequency was 25 Hz. Flexible self-adhesive aluminium

strips were attached at the heel and forefoot of the soles of the shoes. Contact of the strips with the conductive walkway detected the onset of initial contact and toe-off. Signals of the foot contacts were recorded on a portable data acquisition system[2] at a sampling frequency of 800 Hz. The force plate measured the GRF and COP data. Recording, synchronizing and analysis of all measurements were undertaken with a custom-developed Gait Analysis System[3]. The sampling frequency was 100 Hz.

1.3. Procedure

Subjects filled out the Activities-specific Balance Confidence (ABC) scale to obtain information on balance control [16–18]. The ABC scale is a self-efficacy measure that assesses confidence in balance control across 16 activities. A higher score indicates more balance confidence and the maximum score is 100. TF and TT filled in the modified Amputee Activity Score (AAS) to provide insight into their activity level [19,20]. The score lies between −70 and +50. A higher score represents a higher activity level.

Subjects performed 12 trials: 8 on the walkway and 4 on the force plate. In the walkway trials we assessed leading limb preference and single-limb stance duration. In the force plate trials we measured GRF, COP and gait initiation velocity. Subjects started walking from a double-limb standing position on their own initiative. In the first 4 walkway trials no instructions were given on which limb should be used as leading limb. In the following 4 walkway trials subjects had to alternate the leading limb to make sure that each limb was used as the leading one in 4 trials. In the force plate trials subjects started with both limbs placed on the force plate. The position of the feet on the force plate was self-selected. The subjects performed 2 force plate trials with the prosthetic limb leading and 2 trials with the non-affected limb leading.

1.4. Outcome parameters

We determined leading limb preference from the video images of the first 4 trials, in which the leading limb was self-selected. In amputees the percentage of prosthetic leading limb trials was determined, and in AB the percentage of right leading limb trials. Toe-off of the leading limb divided gait initiation in a period of double-limb and single-limb stance. Single-limb stance duration in the trailing limb started at toe-off of the leading limb and ended at initial contact of the leading limb. In AB the mean of the right and left limb was used in the data analysis to minimize the influence of asymmetry between these limbs, whereas in amputees the prosthetic and non-affected limbs were analyzed separately.

Table 1
Subject characteristics, leading limb preference, gait initiation velocity and step execution phase

Group	TF (n = 7)	TT (n = 12)	AB (n = 10)
Sex	6 men, 1 woman	10 men, 2 women	9 men, 1 woman
Age (years)	44.0 ± 14.1	49.6 ± 11.6	45.2 ± 9.4
Body-weight (kg)	81.4 ± 12.4	84.2 ± 8.2	86.5 ± 9.1
Height (cm)	182.6 ± 6.2	180.9 ± 8.5	184.4 ± 6.7
Time since amputation (months)	210.7 ± 158.1	207.8 ± 169.4	
Side amputation	5 right, 2 left	6 right, 6 left	
Cause of amputation	4 trauma, 3 oncology	6 trauma, 2 vascular, 4 oncology	
Prosthetic foot	3 Multiflex, 2 C-walk, 2 dynamic SACH	4 C-walk, 3 dynamic SACH, 2 Quantum, 1 Multiflex, 1 Griessinger multi-axial, 1 SAFE II	
Prosthetic knee	3 Tehlin, 1 C-leg, 1 Ottobock 3R60, 1 Total knee, 1 Proteval		
AAS	35.9 ± 26.9	33.8 ± 26.1	
ABC	83.5 ± 15.9 [*a]	88.4 ± 5.4 [*b]	98.7 ± 1.0
Lead limb preference (%)	71.4 ± 14.9	90.0 ± 4.7	62.5 ± 11.9
Gait initiation velocity (m/s) LP-TN	0.71 ± 0.16 [*a,c]	0.91 ± 0.15 [*c]	
Gait initiation velocity LN-TP	0.69 ± 0.19 [*a]	0.83 ± 0.13 [*b]	1.03 ± 0.17
Single-limb stance (s) TP	0.43 ± 0.18	0.34 ± 0.05	
Single-limb stance TN	0.61 ± 0.10 [*a,c †]	0.43 ± 0.06 [*c †]	0.43 ± 0.05

Mean values and standard deviations of age, body-weight, height, time since amputation, AAS, ABC, gait initiation velocity and single-limb stance duration. Mean values and standard error of leading limb preference in TF and TT for the prosthetic limb, and in AB for the right limb. Sex, side and cause of amputation, and the used prosthetic feet and knees in absolute numbers. Gait initiation velocity in the leading prosthetic and trailing non-affected limb condition (LP-TN) and in the leading non-affected and trailing prosthetic limb condition (LN-TP). Single-limb stance duration of the trailing prosthetic limb (LP) and the trailing non-affected limb (LN). Statistically significant P-values ($P \leq 0.05$) of between group differences are marked with [*]; [*a] for differences between AB and TF and [*b] between AB and TT, and [*c] between TF and TT. Statistically significant differences between the limbs and limb condition within TF and TT are marked with [†].

GRF and COP data were obtained from a single force plate. Consequently, in double-limb stance the resultant GRF and COP of the leading and trailing limbs together was assessed. In amputees 2 limb conditions were distinguished in double limb stance: (1) leading with the prosthetic and trailing with the non-affected limb and (2) leading with the non-affected and trailing with the prosthetic limb. In single-limb stance GRF and COP were executed by the trailing limb alone, resulting in data on the trailing prosthetic and trailing non-affected limb in amputees. In AB in double-

limb stance data of the leading and trailing non-affected limb condition were collected, and in single-limb stance of the trailing non-affected limb alone.

The peak amplitudes of GRF in the vertical (Fz), anteroposterior (Fy) and mediolateral (Fx) directions were obtained (Fig. 1). The first peak (Fz,y,x1) was assessed at the end of double-limb stance at push-off of the leading limb and was produced by the leading and trailing limb together. The second peak (Fz,y,x2) was assessed at the end of single-limb stance at the instant of push-off of the trailing limb and was
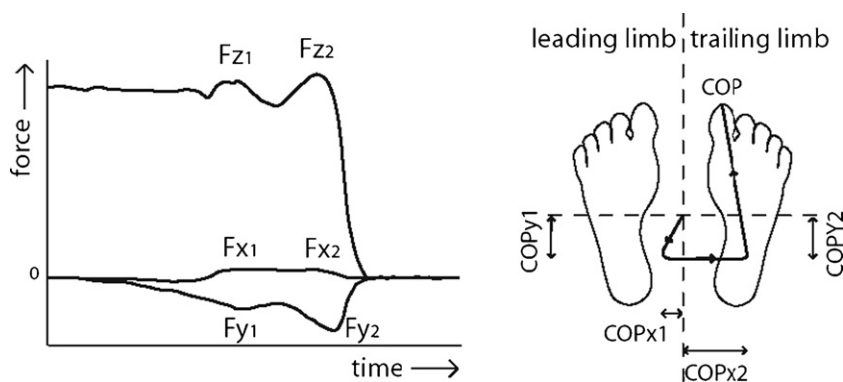

Fig. 1. Schematic representation of the analyzed peak components of the GRF (left) and the measuring points of the COP trajectory (right). Two peak amplitudes of GRF were measured in the vertical (Fz), anteroposterior (Fy), and mediolateral (Fx) direction; the first peak (Fz,y,x1) at push-off of the leading limb in double-limb stance, and the second peak (Fz,y,x2) at push-off of the trailing limb in single-limb stance. The COP path was described by 4 trajectories from the double-limb starting position to: COPy1, the most posterior position on the leading side; COPx1, the most lateral position on the leading side; COPx2, the most lateral position on the trailing side; COPy2, the most posterior position on the trailing side. COPx,y1 coincided with heel-rise of the leading limb and COPx,y2 coincided with leading limb toe-off at the transition from double-limb to single-limb stance.

executed by the trailing limb alone. We expressed GRF as a percentage of body-weight. Gait initiation velocity was calculated by integration of the anterior acceleration from Fy2. The trajectory of the resultant COP in double-limb stance was described by 4 measuring points (Fig. 1).

1.5. Statistical analysis

Normality of the outcome parameters within groups was tested with the Kolmogorov–Smirnov test. For each limb (condition) differences between groups were analyzed by using an ANOVA with study group as main factor, followed by post-hoc analysis according to the least-significant difference (LSD) method. Differences in time since

amputation, AAS and leading limb preference were only tested between TF and TT. The paired *t*-test was used to analyze differences between the non-affected and the prosthetic limb or between the leading prosthetic and leading non-affected limb condition within amputee groups. Level of significance was set on $P \leq 0.05$.

2. Results

Results of the AAS and ABC questionnaires, leading limb preference, gait initiation velocity and single-limb stance duration are presented in Table 1. AAS was similar in TT and TF. AB showed a higher score on the ABC scale than
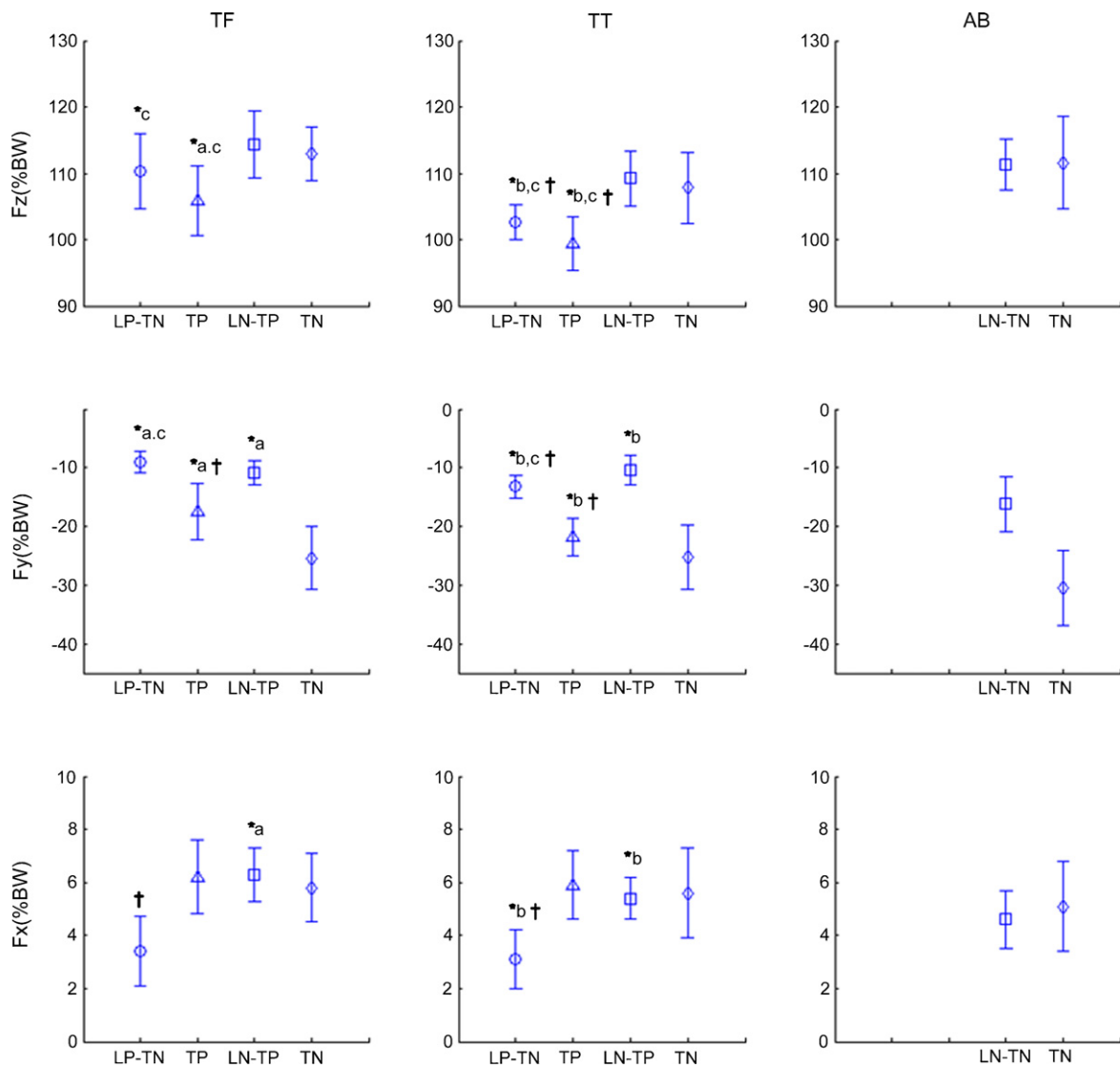

Fig. 2. Mean values and standard deviations of Fx,y,z1 produced in double-limb stance in the leading prosthetic and trailing non-affected limb condition (LP-TN) and in the leading non-affected and trailing prosthetic limb condition (LN-TP) of TF and TT, and in the leading and trailing non-affected limb condition (LN-TN) in AB, and of Fx,y,z2 produced in single-limb stance by the trailing prosthetic limb (TP) and the trailing non-affected limb (TN) separately in TF, TT and AB. Statistically significant *P*-values ($P \leq 0.05$) of between group differences are marked with *; *a for differences between AB and TF, *b between AB and TT, and *c between TF and TT. Statistically significant differences between the limbs and limb condition within TF and TT groups are marked with †. Fz is positive in the upward direction, Fy in the posterior direction and Fx in the trailing limb direction.

TF and TT. In AB there was a preference for the right limb and in TF and TT for the prosthetic limb. Eight out of 12 TT and 4 out of 7 TF started walking with the prosthetic limb consistently in all 4 runs. Compared to AB gait initiation, velocity in the leading prosthetic limb condition was lower in TF and in the leading non-affected limb condition in both amputee groups. Which limb initiated gait did not affect velocity in amputees. In TF the duration of single-limb stance was prolonged in the trailing non-affected limb compared to AB, TT and the trailing prosthetic limb, whereas in TT single-limb stance duration in the trailing prosthetic limb was shorter than in the trailing non-affected limb.

The results of GRF are presented in Fig. 2. TT showed a lower Fz1 in the leading prosthetic limb condition compared to AB, TF, and to Fz1 in the leading non-affected condition. Fz2 of the trailing prosthetic limb was decreased in TF and TT compared to AB. In addition, Fz2 of the trailing prosthetic limb in TT was lower than in TF and compared to Fz2 of the trailing non-affected limb. Fy1 in TF and TT was decreased compared to AB in both limb conditions. In the leading prosthetic limb condition Fy1 in TT was higher than in TF and Fy1 in the leading non-affected limb condition. Fy2 of the trailing prosthetic limb was decreased in TF and TT compared to AB and to Fy2 of the trailing non-affected limb. Fx1 in the leading prosthetic limb condition in TT was decreased compared to AB. In TF and TT Fx1 in the leading non-affected limb condition was increased compared to AB and to Fx1 in the leading prosthetic limb condition.

In Fig. 3 the data of the COP are shown. No differences were seen in COPx1 among the groups. In the leading non-affected limb condition COPx2 in TF and TT shifted more lateral compared to AB and to COPx2 in the leading prosthetic limb condition. In the leading prosthetic limb condition COPy1 in TF and TT was shifted less posteriorly than in AB, and in TT COPy1 was also decreased compared to COPy1 in the leading non-affected limb condition. In TF and TT COPy2 in the leading non-affected limb condition was located anteriorly of the starting position, whereas COPy2 in AB and in the leading prosthetic limb condition was shifted posteriorly. A typical example of the COP trajectories in TF is presented in Fig. 4.
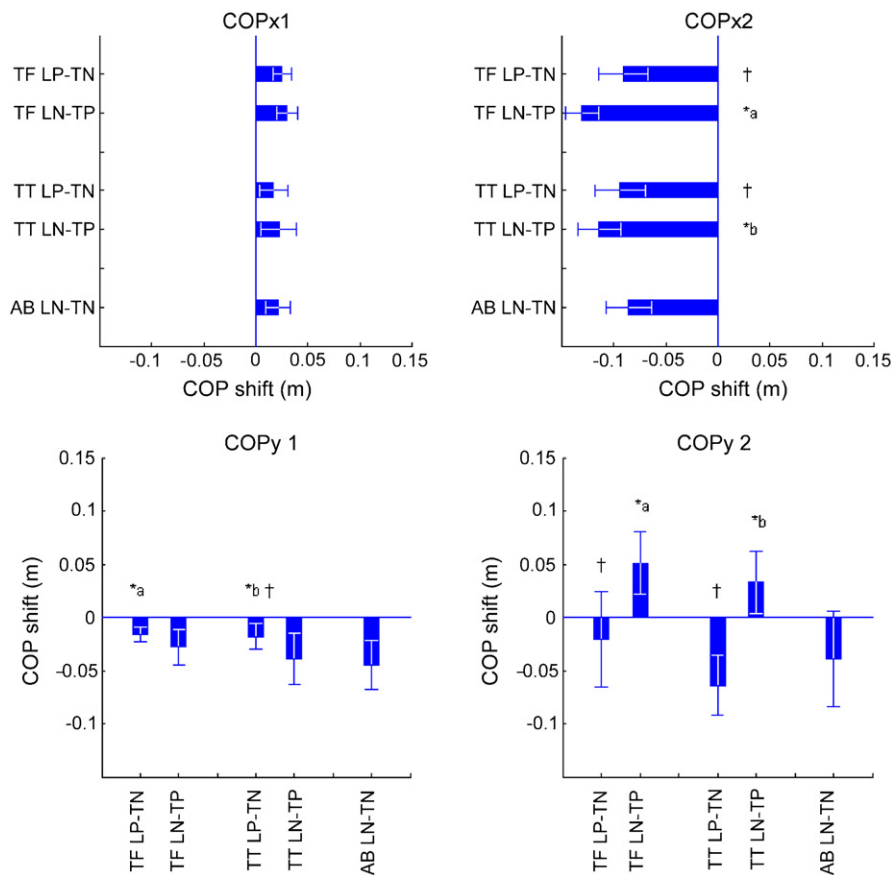

Fig. 3. Mean values and standard deviations of COPx,y1 in early double-limb stance and of COPx,y2 at the end of double-limb stance in the leading prosthetic and trailing non-affected limb condition (LP-TN) and in the leading non-affected and trailing prosthetic limb condition (LN-TP) of TF and TT and in the leading and trailing non-affected limb condition (LN-TN) in AB. Statistically significant P-values ($P \leq 0.05$) of between group differences are marked with [*]; [*]a for differences between AB and TF and [*]b for differences between AB and TT. There were no significant differences between TF and TT. Statistically significant differences between the initiation condition within TF and TT are marked with [†]. COPx is positive in the direction of the leading limb and COPy in the anterior direction.
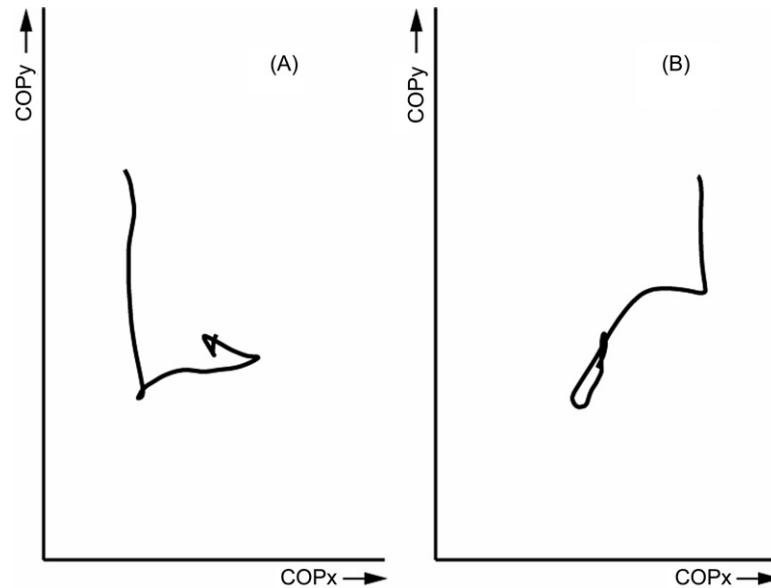
Fig. 4. Example of COP trajectories in a TF subject. (A) The leading right prosthetic limb condition showed a COPy1 and COPy2 shift toward posterior. (B) In the leading left non-affected limb condition COPy1 was intact, but COPy2 displaced toward the forefoot.

3. Discussion

The first goal of this study was to determine limitations in function of the prosthetic limb. For adequate propulsion in gait initiation a posterior COP displacement and an anterior GRF execution are essential. The stiffness of the prosthetic foot, absent ankle dorsiflexors and deficient sensory feedback resulted in a decreased posterior COP shift in amputees. COP trajectory in amputees mostly differed from AB in the leading non-affected limb condition, in which COP was located near the forefoot at the transition to single-limb stance on the trailing prosthetic limb. In the leading prosthetic limb condition a small posterior COP shift could be achieved in amputees, because in double-limb stance the non-affected trailing limb assisted in the execution of postural adjustments. Tokuno et al. [14] came to the same conclusions concerning COP shift in amputees, whereas other authors described a similar COP trajectory in AB and both leading limb conditions of amputees [1,8,21].

The reduced peak anterior GRF in the leading prosthetic limb condition and in the trailing prosthetic limb was caused by the restricted posterior COP shift and the absence of ankle plantar flexors. The trailing limb normally produces the major part of the anterior GRF in the first step [11,22–25]. Peak anterior GRF was predominantly decreased in the trailing prosthetic limb, which corresponded with the absent COP shift in the leading non-affected limb condition. In previous studies a smaller anterior GRF in the prosthetic limb was also seen, most obviously when used as leading limb [1,8,14,15]. As hypothesized, gait initiation velocity was decreased in amputees due to the lower anterior GRF. Velocity at the end of the first step in TF was lower than in TT, especially in the leading non-affected limb condition,

which is in accordance with the smaller peak anterior GRF in TF compared to TT in this condition.

The second aim of this study was to identify adjustment strategies used by amputees in gait initiation. Amputees did not increase peak anterior GRF in the trailing non-affected limb, but prolonged single-limb stance duration in this limb instead. In this manner a larger propulsive impulse could be reached in the trailing non-affected limb. An additional explanation for the long period of single-limb stance in the trailing non-affected limb in TF is provided by the properties of the prosthetic knee: a prosthetic knee generally requires a longer swing phase to reach extension at initial contact. It is known from studies in normal walking that swing phase of the prosthetic limb is prolonged in TF [26,27].

The choice of the leading limb did not influence gait initiation velocity in amputees, which was in agreement with other studies [8,21]. In our study, a lower gait velocity was expected in the leading non-affected limb condition, since most limitations in propulsion were seen in this condition. The only adjustment strategy to enhance propulsion was found in the trailing non-affected limb. However, in previous studies amputees took more time to load the trailing prosthetic limb and increased double-limb stance duration in the leading non-affected limb condition [1,8,14,21]. The consequently larger propulsive impulse may function as an adjustment strategy in the leading non-affected limb condition and explain why gait initiation velocity was independent of the leading limb.

The reduced balance control in amputees, especially in single-limb stance on the prosthetic limb [28], resulted in the occurrence of several adjustment strategies. The limited posterior COP shift could function as an adjustment strategy to prevent a large disequilibrium between COM and COP [14]. Furthermore, placing COP in front of the knee

contributed to prosthetic knee extension in TF to ensure stability in stance. In TT single-limb stance duration in the trailing prosthetic limb was reduced, which could have served as an adjustment strategy to ease balance control. The type of prosthetic foot may have influenced the duration of single-limb stance as well. A prosthetic foot with a roll-over shape that shifts COP quickly toward the toes may force an amputee to place the leading non-affected limb on the floor and thus shorten single-limb stance.

Another adjustment strategy that supported balance was an increased limb-loading on the non-affected side. In amputees vertical GRF peak in the trailing non-affected limb was higher than in the trailing prosthetic limb, which was similar to other studies [1,15]. From the mediolateral GRF and COP data we can conclude that limb-loading in favour of the non-affected limb was already present in double-limb stance. More limb-loading on the trailing limb in double-limb stance requires less mediolateral GRF to shift the COM above the trailing limb in single-limb stance [29]. In amputees, mediolateral GRF in the leading non-affected limb condition was increased, suggesting that a large shift COM toward the trailing prosthetic limb was needed due to the asymmetric limb-loading in double-limb stance. Furthermore, amputees showed a large COP shift toward the trailing prosthetic limb at the instant of transition to single-limb stance. This increased COP shift may endanger stability, because the lacking somatosensory input from the prosthetic limb makes shifting the body-weight accurately above the trailing prosthetic limb difficult. Studies on quiet double-limb standing in amputees reported COP displacement toward the non-affected limb [1,30–32]. In the literature several other explanations for asymmetric limb-loading in amputees have been described: reduced ankle mobility, stump pain, discomfort of the rigid prosthetic socket or prosthetic alignment, poor hip abductor muscle strength, inadequate sensory information in the prosthetic limb, lack of confidence, or habitual stance [32–34].

The preference in amputees to lead gait initiation with the prosthetic limb may indicate an adjustment strategy. Previous research did not result in a unanimous conclusion on leading limb preference in amputees [14,15]. Leading with the prosthetic limb has several advantages: the trailing non-unaffected limb produces most part of the anterior GRF, posterior COP shift is achieved in both double- and single-limb stance, the body-weight is already shifted toward the trailing unaffected limb in double-limb stance, and therefore no large increase in mediolateral COP shift is required. Based on our results, we would advice experienced active amputees to start gait initiation with the prosthetic limb, despite the fact that gait initiation velocity was similar in both leading limb conditions.

The present study contains several limitations. In the TF group the right limb was amputated more often, which may have resulted in a higher leading prosthetic limb preference. In our AB group a preference for the right limb was seen, whereas in previous gait initiation studies on AB

preferences for both limbs were demonstrated [15,22,23]. Due to the long period of time between amputation and participation in the study, inquiring subjects about their leg dominance prior to amputation was considered to be unreliable. Another limitation was that only the first step in gait initiation was studied. Analysis of the second step could alter the advice on leading limb preference. When leading with the prosthetic limb it may be difficult for TF to ensure knee extension at initial contact due to the short swing phase. Furthermore, data on leading limb preference, temporal variables and joint angles were assessed in different trials than COP and GRF data. Since no major differences were seen in the gait pattern among trials, we assumed it was justified to analyze the data together. Finally, stance width may have affected COP shift and GRF in the mediolateral direction [35]. We did not standardize stance width among subjects, because we chose to investigate self-selected gait initiation.

4. Conclusion

The absence of an active flexible ankle joint resulted in limitations in function in the prosthetic limb, which were mostly identical in TF and TT. To achieve adequate propulsion and balance control amputees used several adjustment strategies. Amputees should be advised to initiate gait with the prosthetic limb, since fewer limitations in function were found and less adjustment strategies were needed in this condition. Improvement of prosthetic properties to achieve a more active ankle function could facilitate the gait initiation process.

Conflicts of interest statement

Authors state that no conflicts of interest are present in the research.

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