ORIGINAL RESEARCH

Cross-Slope and Level Walking Strategies During Swing in Individuals With Lower Limb Amputation

Coralie Villa, PhD,[a,b] Isabelle Loiret, MD,[c] Karine Langlois, MSc,[a] Xavier Bonnet, PhD,[d] François Lavaste, PhD,[a,b] Pascale Fodé, MD, MSc,[a] Hélène Pillet, PhD[b]

From the [a]INI, Centre d'Etude et de Recherche sur l'Appareillage des Handicapés, Woippy Cédex; [b]Arts et Metiers ParisTech, Institut de Biomécanique Humaine Georges Charpak, Paris; [c]Centre de médecine physique et de réadaptation Louis Pierquin, IRR-UGECAM Nord-Est 75, Nancy Cedex; and [d]Proteor, Handicap Technologie, Seurre, France.

Abstract

Objective: To quantitatively analyze prosthetic limb swing phase gait strategies used to adapt to cross slopes compared with flat surfaces.
Design: Cross-sectional study.
Setting: Gait laboratory.
Participants: A volunteer sample (N=49) of individuals with transfemoral amputation (n=17), individuals with transtibial amputation (n=15), and able-bodied individuals (n=17).
Interventions: Participants walked on flat and 6° (10%) inclined cross-slope surfaces at a self-selected walking speed.
Main Outcome Measures: Gait speed, step width, sagittal plane kinematics (ankle, knee, hip) on the prosthetic side during swing (uphill limb) and on the contralateral side during stance (downhill limb), frontal plane pelvic kinematics on the prosthetic side during swing, contralateral side ankle power during stance, and timing of gait events.
Results: All groups reduced gait speed and downhill limb knee flexion during the stance phase. Able-bodied participants adjusted their uphill limb ankle flexion during the swing phase. Participants with lower limb amputation used additional adjustments during the swing phase of the prosthetic limb when positioned uphill on cross slopes. Transtibial amputee participants mainly adapted with increased flexion of the residual hip and knee joints. Transfemoral amputee participants primarily compensated using increased pelvic hiking and vaulting gait strategies.
Conclusions: The swing phase of the uphill limb during cross-slope walking results in compensatory mechanisms that should be addressed during rehabilitation to gain confidence and reduce avoidance when encountering cross slopes in daily life.

Level walking can be considered an ideal scenario during outdoor ambulation. However, real-life walking conditions can be much more unfavorable. For example, in urban environments, cross slopes designed for water drainage and garage exits are frequently encountered by pedestrians on sidewalks and roadways. These surfaces are inclined perpendicularly relative to the walking direction (fig 1). These cross slopes result in an apparent leg length discrepancy during gait, estimated at 1.6cm for a 15-cm step width on a 6° (10%) inclined cross slope. According to Walsh et al,[1] a lower limb length discrepancy >0.5cm leads to compensatory gait strategies. Dixon and Pearsall[2] showed that 10 able-bodied (AB) participants, walking on a 10% inclined cross slope, combined a shorter step width with alteration of the lower limb joint flexion angle to shorten the uphill limb and lengthen the downhill limb (see fig 1). No pelvic adjustments in the frontal plane were observed for AB persons walking on a cross slope.[2] The authors[2] theorized that these adaptations facilitate toe clearance during the swing phase of the uphill limb, because a cross slope would induce, without any gait adjustment, a reduction in the distance between the foot and the ground, potentially creating a tripping risk.

Cross-slope perturbations may particularly affect locomotion in individuals with lower limb amputation, especially during the prosthetic limb swing phase when the prosthetic limb is on the uphill side of the cross slope. Prosthetic limb toe clearance is already critical on flat surfaces,[3,4] because it is influenced by knee and hip flexion.[4,5]

Supported by the French National Research Agency (under reference no. ANR- 2010-TECS-020).

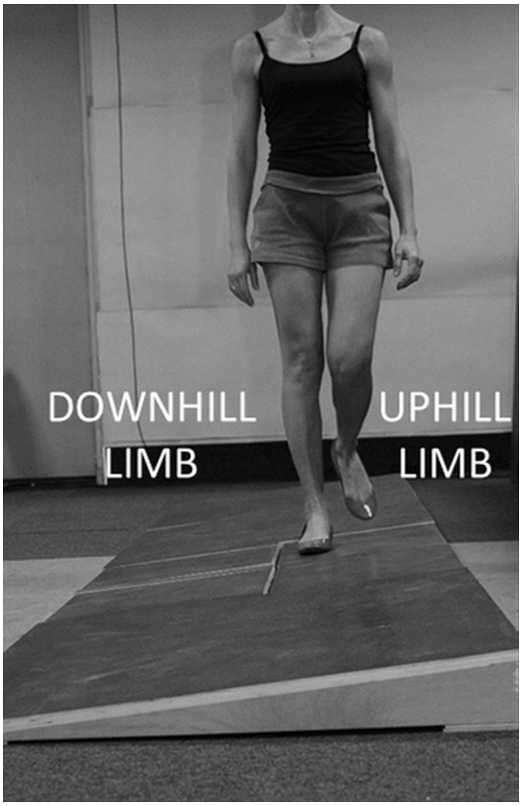

Fig 1 Cross-slope surface setup in the gait laboratory: modular structures made of wood with independent blocks bolted to the force platforms. The upper side/limb is referred to as "uphill"/"uphill limb" and the lower side/limb as "downhill"/"downhill limb."

Particularly, prosthetic knee flexion in transfemoral (TF) amputees can be limited by several factors including suspension systems, prosthetic knee systems, walking speed, and muscle loss.[4,6] To minimize the risk of falling, lower limb amputees use specific gait strategies during level walking: pelvic hike[7,8] and vaulting of the sound ankle (specific to TF amputees).[9,10] However, these strategies are addressed during rehabilitation as they increase energy expenditure and gait asymmetry and could cause back pain and forefoot disorder.[9,11,12]

Few authors have investigated lower limb amputee gait on cross slopes. Villa et al[13] recently showed an increased use of vaulting gait in TF amputees on slopes and cross slopes with the prosthetic limb uphill compared with flat surfaces. Starholm et al[14] suggested that the prosthetic limb swing phase when uphill on cross slopes induced energy-consuming gait strategies in TF amputees to compensate for a "functionally too long" prosthetic limb. In transtibial (TT) amputees, spatiotemporal gait adjustments were investigated with a treadmill using several frontal inclinations.[15,16] A review of the literature has revealed a paucity of descriptive data quantifying gait adjustments (sagittal kinematics, pelvic hike) during the prosthetic swing phase in TT and TF amputees on cross slopes compared with flat surfaces. Thus, the aim of this study was to quantitatively analyze the prosthetic limb swing phase gait strategies used to adapt to cross slopes compared with flat surfaces.

List of abbreviations:

AB **able-bodied**
TF **transfemoral**
TT **transtibial**

This study focused on the swing phase of the prosthetic limb when uphill (and the stance phase of the contralateral limb when downhill). It was hypothesized that (1) lower limb joint sagittal kinematics would be altered compared with level walking to shorten the uphill limb during the swing phase and to lengthen the downhill limb during the stance phase in the AB and amputee groups and (2) pelvic hike and vaulting specific to individuals with lower limb amputation would be greater for the amputee groups on cross slopes compared with flat surfaces. Mean kinematics and timing of gait events were studied in TF amputees, TT amputees, and AB individuals. Considering that TF amputees have the highest level of mobility impairment, individual means were investigated to identify vaulting and/or pelvic hike strategies used for cross-slope walking in this population.

Methods

Participants

Recruitment and data collection were conducted at 2 sites using the same tools. Inclusion criteria were as follows: individuals with unilateral TT or TF amputation, with an activity level of K2 or higher according to Gailey et al.[17] AB individuals had no orthopedic or neurological disorders. All participants were recruited by direct contact on a voluntary basis and provided written informed consent before being included in this study, which was ethically approved by the Paris Ile-de-France VI committee. All participants wore their own shoes and prosthesis whose alignment was checked by the expert prosthetist on site.

Experimental protocol

Fifty-four optoelectronic markers were placed on anatomical landmarks.[18] Marker positions were recorded using an 8-camera motion capture system[a] (Vicon, 100Hz). Ground reaction forces were sampled at 100Hz using 2 force platforms[b] (AMTI) embedded in the floor. Data were recorded when participants stood in a static reference position.[19] Participants walked at a self-selected comfortable speed along an 8-m level surface and then along a 6.2-m cross-slope surface inclined at 6° (10%), which included 4 independent modules bolted to the force platforms (see fig 1).[20] Five successful trials were selected for analysis (ie, when each foot was centrally placed over each force platform).

Data analysis

A 13-segment model was defined by the marker set, and an anatomical frame was embedded in each segment as per Dumas et al.[18] Gait speed (distance over time between the vertebra prominens [C7] marker position at the beginning and end of the prosthetic limb gait cycle) and step width (distance between foot centers upon foot strike projected on the mediolateral axis of the gait reference frame) were computed.

Sagittal plane kinematics of the lower limbs (ankle, knee, hip) and frontal plane kinematics of the pelvis were calculated for both walking conditions.[20] Angles were normalized to the static reference position. Body segment inertial parameters were computed using a personalized geometric model.[21] An inverse dynamics method was used to calculate moments at the lower limb joints. Lastly, joint powers were computed as the dot product between joint moment and joint angular velocity.

This study focused on the swing phase of the prosthetic limb (60%−100% of the prosthetic gait cycle/left limb gait cycle for the AB group), which is consistent with the single support period of the stance phase of the contralateral limb (10%−50% of the contralateral gait cycle/right limb gait cycle for the AB group). The temporal superposition of the prosthetic (uphill) and contralateral (downhill) gait cycles can be observed in figures 2 and 3.

The parameters outlined below were extracted from the kinematic/kinetic variables. First, lower limb joint adjustments in the sagittal plane were investigated in all groups by computing the following (see fig 2):

1. Peak hip flexion angle during the swing phase of the prosthetic limb or the left side of the AB group (see FlexHP in fig 2), hereafter referred to as swing hip flexion parameter
2. Peak hip flexion angle at 30% of the gait cycle during the stance phase of the contralateral limb or the right side of the AB group (see FlexHC in fig2), hereafter referred to as stance hip flexion parameter
3. Peak knee flexion angle during the swing phase of the prosthetic limb or the left side of the AB group (see FlexKP in fig 2), hereafter referred to as swing knee flexion parameter
4. Peak knee flexion angle during the stance phase of the contralateral limb or the right side of the AB group (see FlexKC in fig 2), hereafter referred to as stance knee flexion parameter
5. Ankle plantar flexion angle at 80% of the gait cycle during the swing phase of the prosthetic limb or the left side of the AB group (see FlexAP in fig 2), hereafter referred to as swing ankle flexion parameter

Second, specific gait strategies observed only in individuals with lower limb amputation were investigated in the TT group and TF group by computing the following:

1. Pelvic hike strategy: positive peak pelvis contralateral inclination (angle in the frontal plane) during the swing phase of the

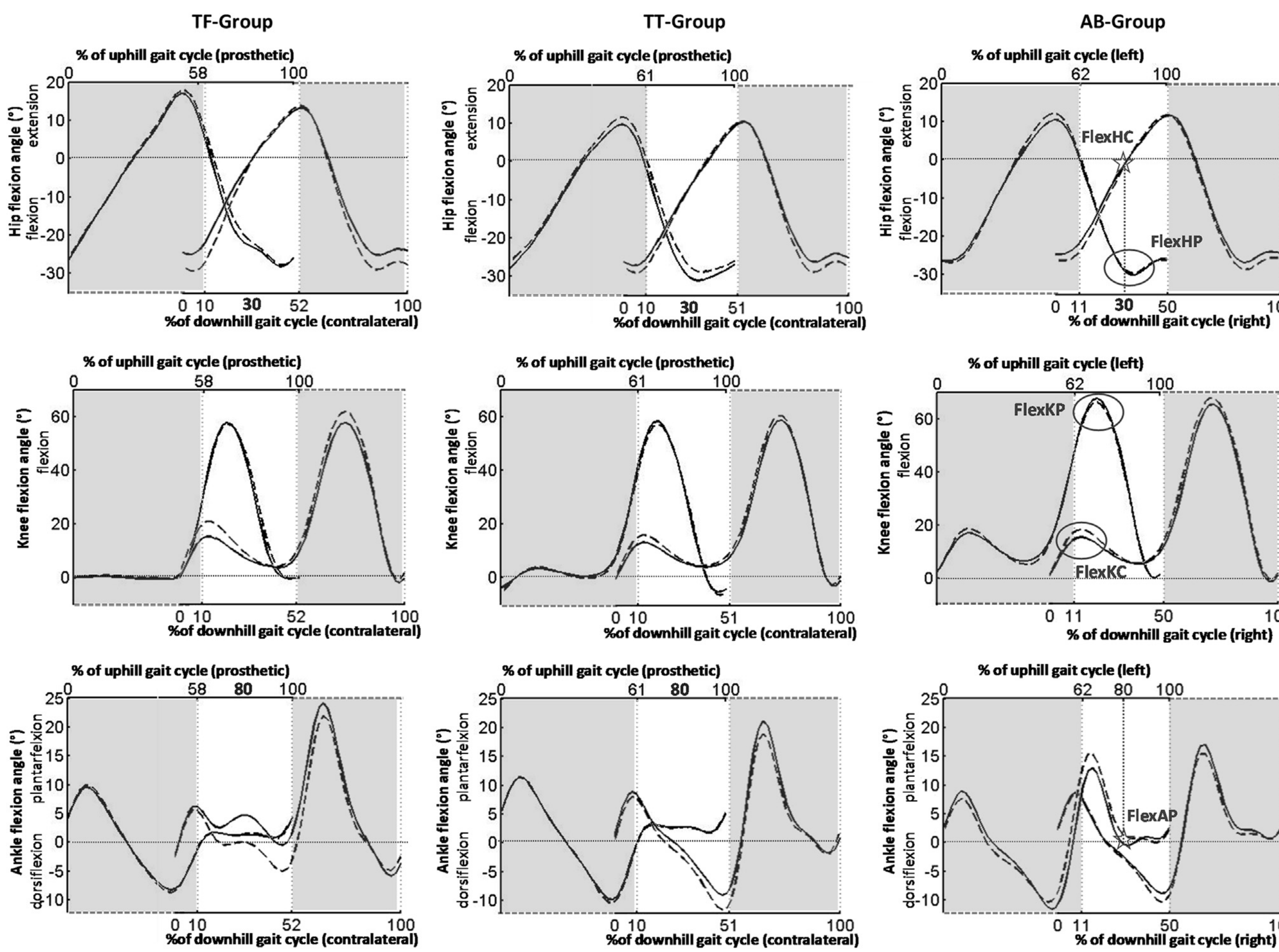

Fig 2 Hip (first row), knee (second row), and ankle (third row) angles in the sagittal plane of the prosthetic limb as a percentage of the prosthetic limb gait cycle (left curves) and of the contralateral limb as a percentage of the contralateral limb gait cycle (right curves) on level ground (dashed line) and cross slopes (line). White zone corresponds to the swing phase of the prosthetic limb and the single support period of the stance phase of the contralateral limb. The TF group is in the first column, the TT group in the second column, and the AB group in the third column. In the AB group, the left limb is in the swing phase on level ground (dashed line) and uphill (line) and the right limb is in the single support period of the stance phase on level ground (dashed line) and downhill (line). Toe off and heel strike of the prosthetic (or left) limb are indicated in the prosthetic (or left) and contralateral (or right) limb gait cycle on each graph. In the third column the extracted parameters FlexHP, FlexHC, FlexKP, FlexKC, and FlexAP are illustrated. Abbreviations: FlexAP, swing ankle flexion parameter; FlexHC, stance hip flexion parameter; FlexHP, swing hip flexion parameter; FlexKC, stance knee flexion parameter; FlexKP, swing knee flexion parameter.

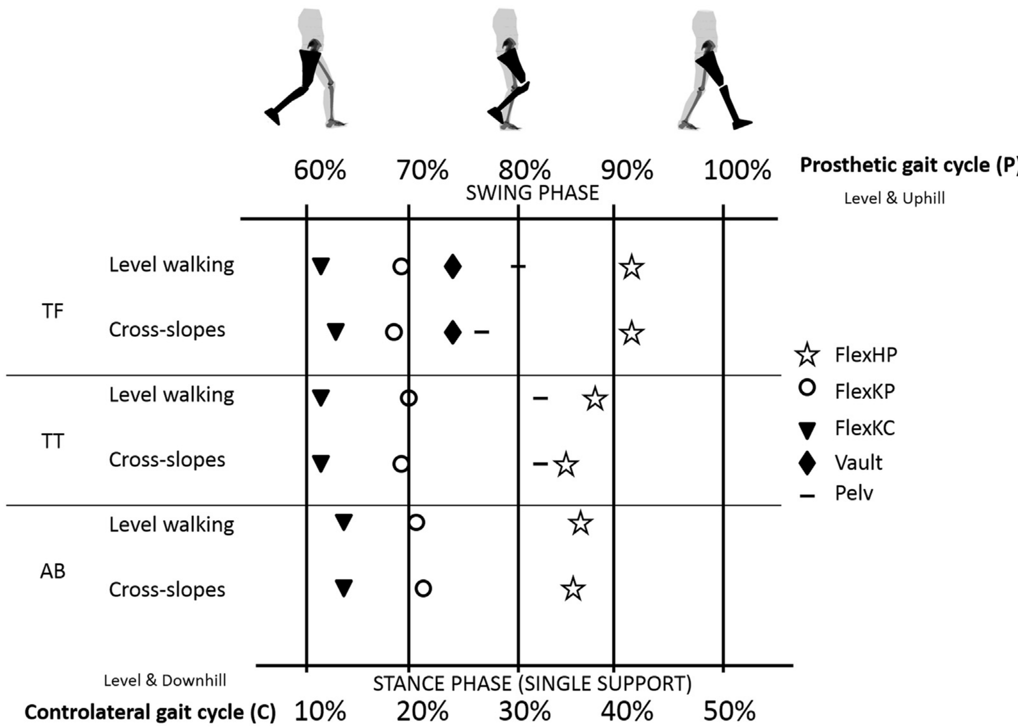

Fig 3 Average timing of FlexHP, FlexKP, and Pelv parameters in the prosthetic limb gait cycle (flat surface and uphill on cross slope) and FlexKC and Vault parameters in the contralateral limb gait cycle (flat surface and downhill on cross slope). Abbreviations: FlexHP, swing hip flexion parameter; FlexKC, stance knee flexion parameter; FlexKP, swing knee flexion parameter; Pelv, hip hiking parameter; Vault, vaulting parameter.

prosthetic gait cycle (see Pelv in fig 4), as suggested by Goujon-Pillet et al,[7] hereafter referred to as hip hiking parameter

2. Vaulting strategy: peak ankle flexion power generated by the contralateral limb during the stance phase between 20% and 40% of the contralateral limb gait cycle and >.15W/kg for the vaulting strategy, as suggested by Drevelle et al.[10] It is hereafter referred to as vaulting parameter.

Timing of parameters in the gait cycle was computed for both situations as a percentage of the prosthetic gait cycle for the swing knee flexion parameter, swing hip flexion parameter, and hip hiking parameter and as a percentage of the contralateral gait cycle for swing knee flexion parameter and vaulting parameter.

For descriptive purposes, parameter and timing variations were computed for each participant as the difference between the values obtained during cross-slope walking and the values obtained during level walking. The mean and SD of the variations were then computed for each group.

Statistical analysis

The effect of the walking condition was assessed separately for each group of participants (TF group, TT group, AB group).

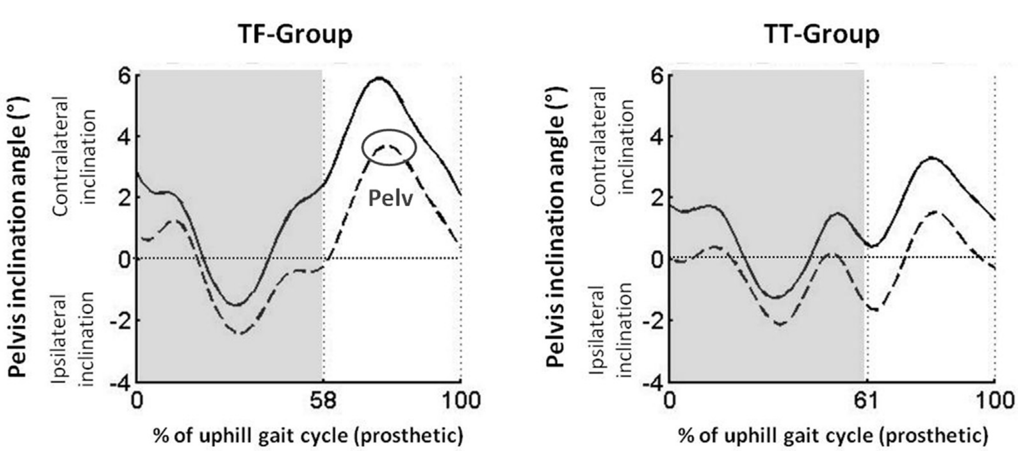

Fig 4 Average pelvis angle in the frontal plane during the prosthetic limb gait cycle in the TF group and TT group on level ground (dashed line) and cross slopes (line). Abbreviation: Pelv, hip hiking parameter.

Table 1 TF and TT amputee participants

Patient	Involved Side	Amputation Cause	Residual Limb Length (cm)	Residual Limb Length/Sound Limb Ratio (%)	Amputation Level	Time Since Amputation (y)	Socket	Suspension	Prosthetic Knee	Prosthetic Foot
TF1	Left	Trauma	19	50	Medium	16	Ischial containment	Locking pin	C-Leg*	1C40 C-Walk*
TF2	Right	Trauma	46	121	Gritti	21	Knee disarticulation	Suction	C-Leg*	Flex walk†
TF3	Left	Trauma	37	82	Inferior	16	Ischial containment	Suction	C-Leg*	1C60 Triton*
TF4	Right	Tumor	41	105	Gritti	1	Knee disarticulation	Suction	C-Leg*	Flex walk†
TF5	Right	Trauma	48	98	Gritti	3	Knee disarticulation	Suction	OH5‡	Multiflex§
TF6	Left	Trauma	38	81	Inferior	2	Ischial containment	Suction	Sensor‖	Variflex†
TF7	Left	Trauma	35	74	Inferior	2	Ischial containment	Suction	C-Leg*	1C40 C-Walk*
TF8	Right	Trauma	46	110	Gritti	2	Knee disarticulation	Suction	KX6§	1C60 Triton*
TF9	Left	Trauma	36	86	Inferior	NI	Ischial containment	Suction	C-Leg*	Flex walk†
TF10	Left	Trauma	31	76	Inferior	NI	Ischial containment	Suction	C-Leg*	Flex walk†
TF11	Left	Tumor	11	24	Superior	NI	Ischial containment	Locking pin	C-Leg*	1C40 C-Walk*
TF12	Left	Trauma	27	59	Medium	3	Ischial containment	Suction	C-Leg*	Flex walk†
TF13	Left	Trauma	27	71	Inferior	34	MAS	Suction	RheoKnee†	Reflex Shock†
TF14	Left	Trauma	34	77	Inferior	5	Ischial containment	Suction	Hybrid Knee‖	Variflex†
TF15	Left	Trauma	26	67	Medium	15	MAS	Suction	RheoKnee†	Reflex Rotate†
TF16	Left	Trauma	34	81	Inferior	4	MAS	Suction	Genium*	Elation†
TF17	Left	Trauma	36	86	Inferior	16	Ischial containment	Suction	Hybrid Knee‖	Flex walk†
TT1	Left	Trauma	12	27	Superior	23	TSB	Thigh Lacer	NA	Reflex Rotate†
TT2	Left	Trauma	26	63	Medium	3	TSB	Suction	NA	Echelon§
TT3	Left	Trauma	27	62	Medium	16	TSB	Suction	NA	Variflex†
TT4	Left	Tumor	11	27	Superior	21	TSB	Locking pin	NA	Variflex†
TT5	Right	Trauma	13	30	Superior	20	TSB	Suction Sleeve	NA	1C30 Trias*
TT6	Left	Trauma	15	36	Medium	4	TSB	Locking pin	NA	1C30 Trias*
TT7	Left	Trauma	14	33	Superior	5	TSB	Suction Sleeve	NA	Propriofoot†
TT8	Left	Tumor	15	38	Medium	5	TSB	Suction Sleeve	NA	Cadence HP¶
TT9	Right	Trauma	11	26	Superior	43	TSB	Suction Sleeve	NA	1C30 Trias*
TT10	Right	Congenital	15	32	Superior	Not appropriate	TSB	Locking pin	NA	Variflex†
TT11	Right	Trauma	16	36	Medium	1	TSB	Suction Sleeve	NA	Reflex Shock†
TT12	Right	Trauma	15	33	Superior	7	TSB	Suction Sleeve	NA	Reflex Shock†
TT13	Left	Trauma	19	48	Medium	5	TSB	Suction Sleeve	NA	Sure-flex†
TT14	Left	Trauma	17	39	Medium	19	TSB	Suction Sleeve	NA	Reflex Shock†
TT15	Left	Congenital	NI	NI	Inferior	Not appropriate	TSB	NI	NA	Flex walk†

NOTE. Residual limb length: (TT) lateral epicondyle of the knee to bone extremity/(TF) greater trochanter to bone extremity; Sound limb length: (TT) lateral epicondyle of the knee to lateral malleolus/(TF) greater trochanter to lateral epicondyle of the knee.

Abbreviations: Gritti, knee disarticulation amputation; MAS, Marlo Anatomical Socket; NA, not applicable; NI, not informed; TBS, total surface-bearing socket.

* Ottobock.

† Ossur.

‡ Medi.

§ Endolite.

¶ Seattle.

‖ Nabtesco.

A Wilcoxon signed-rank test (small sample size) for 2 paired samples was used between walking conditions (level walking/downhill or level walking/uphill) depending on the parameter. When the null hypothesis was rejected at $P<.05$, a significant difference between conditions was considered and the size of the effect was assessed (difference between the proportion of favorable and unfavorable rank sums, ranging from 0 to 1) as per Kerby.[22]

Results

Participants

Seventeen TF amputees (16 men and 1 woman; mean age, 38±11y; mean weight, 74±11kg; mean height, 174±8cm), 15 TT amputees (14 men and 1 woman; mean age, 51±12y; mean weight, 84±14kg; mean height, 176±7cm), and 17 AB individuals (9 men and 8 women; mean age, 48±18y; mean weight, 67±12kg; mean height, 171±10cm) participated in this study. Amputation and fitting details of TT and TF participants are provided in table 1.

Spatiotemporal parameters

Gait speed significantly decreased during cross-slope walking compared with level walking for all groups (TF group: −0.12±0.10m/s, from 1.23±0.14 to 1.11±0.17m/s; $P<.001$; TT group: −0.13±0.11m/s, from 1.22±0.16 to 1.09±0.15m/s; $P=.003$; AB group: 0.16±0.12m/s, from 1.28±0.12 to 1.12±0.14m/s; $P<.001$). Step width was no different between walking conditions for all groups (TF group: $P=.068$; TT group: $P=.107$; AB group: $P=.868$).

Lower limb joint kinematic adjustments

Lower limb joint kinematics and extracted parameters are provided in figure 2 and table 2. In the AB group, there were significant decreases during cross-slope walking compared with level walking, in the stance knee flexion parameter (−3°±3° at 14%±2% of the downhill limb gait cycle) and in the swing ankle flexion parameter (2°±2° at 80% of the uphill limb gait cycle). In the TT group, significant increases in the swing knee flexion parameter (1°±2°) and the swing hip flexion parameter (2°±2°) were observed for the prosthetic lower limb during swing when uphill on the cross slope compared with flat surfaces. A significant decrease in the stance knee flexion parameter (−3°±3°) was also observed for the contralateral limb during stance when downhill on the cross slope compared with flat surfaces. In the TF group, results only showed a significant decrease in the stance knee flexion parameter (−4°±3°) for the contralateral limb during stance when downhill on the cross slope compared with flat surfaces.

Specific gait strategy adjustments

Pelvis kinematics in the frontal plane for the TT group and TF group indicated that the average inclination during the swing phase of the prosthetic limb was toward the contralateral side on level ground, with amplification on cross slopes (see fig 4). In the TT group, an increase in pelvic inclination toward the contralateral side was observed at the beginning of the swing phase and was maintained throughout the prosthetic swing phase. Maximum lateral pelvis tilt (hip hiking parameter) occurred at 83% of the prosthetic gait cycle and significantly increased by ∼2°±1° compared with level walking (see fig 4 and table 2). No changes

Table 2 Lower limb joint kinematic adjustments and specific gait strategy adjustments in all groups

Parameter	Side	Group	Level Ground	Cross Slopes	*P*	Effect Size
Lower limb joints kinematic adjustments						
Swing hip flexion parameter (deg) (FlexHP in fig 2)	Prosthetic	TF	−29±3	−29±5	.924	NA
(level and uphill)	Prosthetic	TT	−30±6	−32±6*	.006*	0.77
	Left	AB	−30±5	−30±5	.534	NA
Swing knee flexion parameter (deg) (FlexKP in fig 2)	Prosthetic	TF	58±10	58±12	.698	NA
(level and uphill)	Prosthetic	TT	58±8	59±8*	.004*	0.94
	Left	AB	67±5	68±6	.066	NA
Swing ankle flexion parameter (deg) (Flex AP in fig 2)	Prosthetic	TF	2±2	2±2	.766	NA
(level and uphill)	Prosthetic	TT	3±1	3±1	>.99	NA
	Left	AB	1±4	0±5*	.012*	0.63
Stance hip flexion parameter (deg) (FlexHC in fig 2)	Contralateral	TF	−1±4	−2±4	.550	NA
(level and downhill)	Contralateral	TT	−7±4	−7±5	.931	NA
	Right	AB	−3±4	−3±4	.445	NA
Stance knee flexion parameter (deg) (FlexKC in fig 2)	Contralateral	TF	20±5	15±6*	<.001*	1.00
(level and downhill)	Contralateral	TT	16±6	14±6*	.002*	0.93
	Right	AB	19±5	16±5*	<.001*	0.73
Specific gait strategies						
Hip hiking parameter (deg) (Pelv in fig 4)	Prosthetic	TF	4±2	6±3*	<.001*	0.96
(level and uphill)	Prosthetic	TT	2±1	4±2*	.001*	0.95
Vaulting parameter (W/kg) (level and downhill)	Contralateral	TF	0.18±0.29	0.39±0.48*	.011*	0.70
	Contralateral	TT	−0.10±0.09	−0.10±0.07	.792	NA

NOTE. Values are mean ± SD.
Abbreviation: NA, not applicable.
* Indicates significant difference ($P<.05$) between the values obtained during cross-slope walking and those obtained during level walking, and the effect size is provided.

were found in the vaulting parameter. In the TF group, the hip hiking parameter and the vaulting parameter increased significantly by ∼2°±2° and .22±.28W/kg, respectively (see table 2).

Parameter timing during the gait cycle

Timing of extracted parameters in gait cycle are provided in figure 3. No significant changes in parameter timing were observed in the AB group between walking conditions. In the TT group, only the swing hip flexion parameter was observed significantly earlier ($P=.039$) during the prosthetic limb gait cycle when uphill on the cross slope (85%±5%) compared with flat surfaces (88%±6%). Lastly, in the TF group, the hip hiking parameter occurred significantly earlier ($P=.012$) in the prosthetic gait cycle on the cross slope (77%±9%) compared with flat surfaces (80%±7%).

Individual strategy adjustments in the TF group

In the TF group, individual strategies were investigated for the hip hiking and vaulting parameters in 17 participants (fig 5). First, during level walking, the hip hiking parameter was >0° for 16 participants and the vaulting parameter was ≥.15W/kg for 8 participants. More specifically, 1 participant demonstrated only a vaulting parameter ≥.15W/kg (participant TF14), 9 participants showed only a positive hip hiking parameter (participants TF2, 3, 4, 5, 7, 8, 9, 10, 16), and 7 participants showed both a positive hip hiking parameter and a vaulting parameter ≥.15W/kg (participants TF1, 6, 11, 12, 13, 15, 17) (fig 5 and see table 1).

Second, on the cross slope, the hip hiking parameter was again positive for the same 16 participants and higher compared to that on the flat surface for 13 of them (the increase ranged from 1° to 6°). In addition, the vaulting parameter increased on cross slopes for the 8 participants whose values were already ≥.15W/kg on the flat surface (the increase ranged from .10 to .89W/kg). Furthermore, 3 participants (TF7, 8, 9) demonstrated a vaulting parameter ≥.15W/kg for cross-slope walking but not for level walking. No participants had both a negative hip hiking parameter and a vaulting parameter below .15W/kg for either walking condition.

These data were used to identify 3 adjustment profiles (compensatory strategies) that TF amputees adopted for walking on cross-slope surfaces (see fig 5):

1. Profile 1: Only the vaulting parameter increased for 5 (TF6, 8, 11, 13, 14) of the 17 participants (30%)
2. Profile 2: Only the hip hiking parameter increased for 6 (TF2, 3, 4, 5, 10, 16) of the 17 participants (35%)
3. Profile 3: Both the hip hiking parameter and vaulting parameter increased for 6 (TF1, 7, 9, 12, 15, 17) of the 17 participants (35%).

Discussion

The aim of this study was to quantitatively analyze prosthetic limb swing phase gait strategies used to adapt to cross slopes compared with flat surfaces.

AB individuals used sagittal adjustments such as reduced maximum downhill knee flexion angle during stance and reduced uphill ankle plantar flexion angle during swing to compensate for leg length discrepancy during the uphill limb swing phase on cross slopes. These features were consistent with the study of Dixon and Pearsall[2] even if some other adjustments such as increased step width or increased uphill hip flexion were not supported by the results of the present study. In addition, no changes in parameter timing were observed in the AB group between level and cross-slope walking.

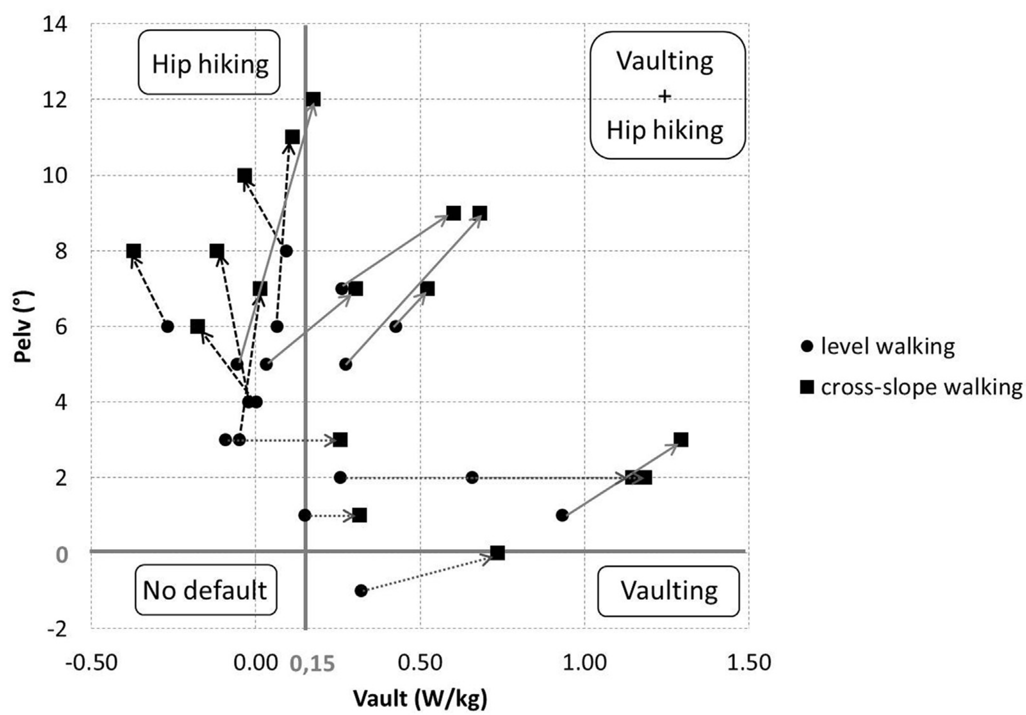

Fig 5 Individual strategy adjustments in the TF group: individual values for Pelv (y-axis) and Vault (x-axis) parameters for each participant in the TF group on level ground (dot) and cross slopes (square). The 2 gray lines indicate the threshold defined for pelvic hike (0°) and vaulting (.15W/kg). Individual adjustments are indicated by arrows. Three profiles are highlighted: profile 1 (dotted arrows), profile 2 (dashed arrows), and profile 3 (continuous arrows). Abbreviations: Pelv, hip hiking parameter; Vault, vaulting parameter.

For lower limb amputees, sagittal adjustments were also observed. Notably, all participant groups shared a similar strategy that tended to lengthen the downhill contralateral side at the very beginning of the single support period during the stance phase by decreasing the downhill knee flexion (stance knee flexion parameter). This reduction was associated with a decrease in gait speed. However, on the prosthetic side, sagittal adjustment of the ankle was limited because of the inability of the prosthetic ankles to actively flex during the swing phase.[23] To compensate for this limitation, TT amputees could use their residual knee and hip joints during the swing phase by increasing their flexion on cross slopes compared with flat surfaces. Conversely, results showed that TF amputees did not resort to adjustments of their residual hip flexion angle on cross slopes. These results are consistent with a previous study investigating adjustment strategies in TT and TF amputees ascending a 5% slope inclined in the sagittal plane.[24]

An additional strategy involving the frontal plane was investigated in the lower limb amputee populations. The pelvic hike strategy was observed in both groups during level walking, which is consistent with previous results[7,8] and was amplified on cross slopes. Compared with level walking, a 2° increase in pelvic inclination was observed during cross-slope walking. This corresponds to a difference of ∼2cm in height between pelvic iliac spines with a 30-cm-wide pelvis and can even be detected during observational gait analysis. The results also highlighted a timing adjustment in the gait cycle, with this frontal plane strategy in the TF group.

In addition, the TF group completed these strategies by using their contralateral ankle during the stance phase. This strategy, known as vaulting gait, has already been studied in a previous article.[13] In the present study, a case-by-case investigation of vaulting gait and pelvic hike strategies was performed on this population with the greatest difficulty. The investigation revealed 3 profiles for examining individual adjustment patterns between level and cross-slope walking during the prosthetic swing phase: one-third of the TF group amplified pelvic hike, another third amplified or started vaulting, and the last third amplified both strategies. Consequently, the disturbance caused by cross slopes tends to emphasize these specific gait strategies to facilitate toe clearance, making them visible during gait.

The results suggest that cross slopes should be considered in rehabilitation programs to identify compensatory mechanisms (pelvic hike, vaulting, altered residual hip/knee kinematics) that may not be observed during level walking. Caregivers currently seek to minimize such asymmetric compensations to avoid increased energy expenditure[12] and potentially induced secondary conditions (joint/lumbar pain).[9,11] This objective can be accomplished through proper prosthetic setting,[9] musculoskeletal conditioning,[11] and motor learning of the sensations and tasks associated with the swing phase of the prosthetic limb (where the foot is, when and how to flex the prosthetic knee, hip control) until gait automaticity with the prosthesis is restored.[25-27] Such a rehabilitation process could be applied to cross slopes to minimize falling factors (by increasing confidence, decreasing cognitive load, and reducing asymmetry and deviations)[28] and sidestepping in daily living environments. Other measures, including active dorsiflexion during swing with a prosthetic ankle design, may also help with locomotion on cross slopes.[29]

Study limitations

This study was limited to analysis of lower limb and pelvis strategies. Trunk and upper limb compensations should also be investigated. Risk of type I error may be accentuated because of a large number of paired tests. The TT group participants were younger than the TF group participants, which may have influenced the results. Both groups were largely male and moderately active or active individuals (inclusion criteria). Because most participants in the TF group had long or medium amputation levels, it could be interesting to widen the scope of this study to include more participants with a short residual limb length because muscular and joint range of motion limitations might worsen gait speed variations and gait deviations on cross slopes.

Conclusions

This study provided new quantitative data on the locomotion of individuals with lower limb amputation on flat surfaces and cross slopes during the prosthetic limb swing phase. Not only were average behaviors investigated but individual adjustments were also presented for a TF amputee population with the most hindered gait. The swing phase of the uphill limb during cross-slope walking results in compensatory mechanisms that should be addressed in rehabilitation to improve confidence and reduce avoidance when encountering cross slopes in daily life.

Suppliers

a. Camera motion capture system; Vicon Motion Systems.
b. Force platforms; Advanced Mechanical Technology Inc.

Keywords

Amputees; Gait; Locomotion; Pelvis; Rehabilitation

Corresponding author

Coralie Villa, PhD, INI, Centre d'Etude et de Recherche sur l'Appareillage des Handicapés, 47 rue de l'échat, 94000 Créteil, France. *E-mail address:* coralie.villa@invalides.fr.

References

1. Walsh M, Connolly P, Jenkinson A, O'Brien T. Leg length discrepancy—an experimental study of compensatory changes in three dimensions using gait analysis. Gait Posture 2000;12:156-61.
2. Dixon PC, Pearsall DJ. Gait dynamics on a cross-slope walking surface. J Appl Biomech 2010;26:17-25.
3. DeAsha AR, Buckley JG. The effects of walking speed on minimum toe clearance and on the temporal relationship between minimum clearance and peak swing-foot velocity in unilateral trans-tibial amputees. Prosthet Orthot Int 2015;39:120-5.
4. Jaegers SM, Arendzen JH, Jongh HJ. Prosthetic gait of unilateral transfemoral amputees: a kinematic study. Arch Phys Med Rehabil 1995;76:736-43.
5. Nolan L, Lees A. The functional demands on the intact limb during walking for active trans-femoral and trans-tibial amputees. Prosthet Orthot Int 2000;24:117-25.
6. Perry J. Gait analysis: normal and pathological function. Thorofare: SLACK Incorporated; 1992.

7. Goujon-Pillet H, Sapin E, Fodé P, Lavaste F. Three-dimensional motions of trunk and pelvis during transfemoral amputee gait. Arch Phys Med Rehabil 2008;89:87-94.
8. Michaud SB, Gard SA, Childress DS. A preliminary investigation of pelvic obliquity patterns during gait in persons with transtibial and transfemoral amputation. J Rehabil Res Dev 2000;37:1-10.
9. Smith DG, Michael JW, Bowker JH. Atlas of amputations and limb deficiencies. Rosemont: American Academy of Orthopaedic Surgeons; 2002.
10. Drevelle X, Villa C, Bonnet X, Loiret I, Fodé P, Pillet H. Vaulting quantification during level walking of transfemoral amputees. Clin Biomech 2014;29:679-83.
11. Gailey R, Allen K, Castles J, Kucharik J, Roeder M. Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use. J Rehabil Res Dev 2008;45:15-30.
12. Su PF, Gard SA, Lipschutz RD, Kuiken TA. Gait characteristics of persons with bilateral transtibial amputations. J Rehabil Res Dev 2007;44:491-502.
13. Villa C, Drevelle X, Bonnet X, et al. Evolution of vaulting strategy during locomotion of individuals with transfemoral amputation on slopes and cross-slopes compared to level walking. Clin Biomech 2015;30:623-8.
14. Starholm IM, Gjovaag T, Mengshoel AM. Energy expenditure of transfemoral amputees walking on a horizontal and tilted treadmill simulating different outdoor walking conditions. Prosthet Orthot Int 2010;34:184-94.
15. Hak L, van Dieën JH, van der Wurff P, et al. Walking in an unstable environment: strategies used by transtibial amputees to prevent falling during gait. Arch Phys Med Rehabil 2013;94:2186-93.
16. Sinitski EH, Lemaire ED, Baddour N, Besemann M, Dudek NL, Hebert JS. Fixed and self-paced treadmill walking for able-bodied and transtibial amputees in a multi-terrain virtual environment. Gait Posture 2015;41:568-73.
17. Gailey RS, Roach KE, Applegate EB, et al. The amputee mobility predictor: an instrument to assess determinants of the lower-limb amputee's ability to ambulate. Arch Phys Med Rehabil 2002;83: 613-27.
18. Dumas R, Chèze L, Verriest JP. Adjustments to McConville et al. and Young, et al. body segment inertial parameters. J Biomech 2007;40:543-53.
19. Pillet H, Villa C, Langlois K, et al. [Prosthetic fitting of lower limb amputees in limiting daily living situations] [French]. Kinésithér Scient 2016;0573:19-29.
20. Pillet H, Drevelle X, Bonnet X, et al. APSIC: training and fitting amputees during situations of daily living. Innov Res Biomed Eng 2014;35:60-5.
21. Pillet H, Bonnet X, Lavaste F, Skalli W. Evaluation of force plate-less estimation of the trajectory of the centre of pressure during gait: comparison of two anthropometric models. Gait Posture 2010;31:147-52.
22. Kerby DS. The simple difference formula: an approach to teaching nonparametric correlation. Compr Psychol 2014;3:1.
23. Fradet L, Alimusaj M, Braatz F, Wolf SI. Biomechanical analysis of ramp ambulation of transtibial amputees with an adaptive ankle foot system. Gait Posture 2010;32:191-8.
24. Vrieling AH, van Keeken HG, Schoppen T, et al. Uphill and downhill walking in unilateral lower limb amputees. Gait Posture 2008; 28:235-42.
25. Sawers A, Hahn ME, Kelly VE, Czerniecki JM, Kartin D. Beyond componentry: how principles of motor learning can enhance locomotor rehabilitation of individuals with lower limb loss—a review. J Rehabil Res Dev 2012;49:1431-42.
26. Geurts AC, Mulder TW. Reorganisation of postural control following lower limb amputation: theoretical considerations and implications for rehabilitation. Physiother Theor Pract 1992;8:145-57.
27. Schmalz T, Bellmann M, Proebsting E, Blumentritt S. Effects of adaptation to a functionally new prosthetic lower-limb component: results of biomechanical tests immediately after fitting and after 3 months of use. J Prosth Orthot 2014;26:134-43.
28. Miller WC, Speechley M, Deathe B. The prevalence and risk factors of falling and fear of falling among lower extremity amputees. Arch Phys Med Rehabil 2001;82:1031-7.
29. Rosenblatt NJ, Bauer A, Rotter D, Grabiner MD. Active dorsiflexing prostheses may reduce trip-related fall risk in people with transtibial amputation. J Rehabil Res Dev 2014;51:1229-42.