Evolution of vaulting strategy during locomotion of individuals with transfemoral amputation on slopes and cross-slopes compared to level walking

Coralie Villa [a,b,*], Xavier Drevelle [a], Xavier Bonnet [c], François Lavaste [a,b], Isabelle Loiret [d], Pascale Fodé [a], Hélène Pillet [b,**]

[a] Institution Nationale des Invalides Centre d'Etude et de Recherche sur l'Appareillage des Handicapés, BP 50719, 57147 Woippy Cedex, France
[b] Arts et Metiers ParisTech, Institut de Biomécanique Humaine Georges Charpak, 151 boulevard de l'Hôpital, 75013 Paris, France
[c] PROTEOR, 6 rue de la redoute 21250 Seurre, France
[d] Centre de médecine physique et de réadaptation Louis Pierquin IRR-UGECAM, Nord-Est 75, Boulevard Lobau, CS 34209, 54042 Nancy Cedex, France

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A B S T R A C T

Background: Vaulting is a walking strategy qualitatively characterized in clinics by the sound ankle plantiflexion in midstance to assist prosthetic foot clearance. Even though potentially harmful, this strategy is often observed among people with transfemoral amputation to secure clearance of the prosthetic limb during swing phase. The aim of the study is to provide a quantitative analysis of the evolution of the vaulting strategy in challenging situations of daily living.
Methods: 17 persons with transfemoral amputation and 17 able-bodied people participated in the study. Kine-matic and kinetic gait analyses were performed for level walking, 10% inclined cross-slope walking, 5% and 12% inclined slope ascending. To study vaulting strategy, peak of generated power at the sound ankle at midstance was identified and quantified in the different walking situations. In particular, values were compared to a vaulting threshold corresponding to a peak of generated power superior to 0.15 W/kg.
Findings: The vaulting threshold was exceeded for a larger proportion of people with amputation during cross-slope locomotion and slope ascent than during level walking. In addition, magnitude of the peak of generated power increased significantly compared to level walking in these situations.
Interpretation: Vaulting seems to be widely used by patients with transfemoral amputation in daily living situa-tions. The number of patients using vaulting increased with the difficulty of the walking situation. Results also suggested that patients could dose the amount of vaulting according to gait environment to secure prosthetic toe clearance. During rehabilitation, vaulting should also be corrected or prevented in daily living tasks.

1. Introduction

People with transfemoral amputation have lost their knee and ankle joints. Prosthetic components are restoring part of the missing joints functions. For example, during swing phase of gait, the prosthetic knee must permit foot clearance. Prosthetic knee flexion during swing phase depends on hip flexor muscle activity from the end of the stance phase (maximum of hip flexion moment) and on the prosthetic component properties (e.g., friction knee vs microprocessor-controlled knee) (Bellmann et al., 2010; Vrieling et al., 2008). In the case of insufficient hip and prosthetic knee flexion or inadequate timing of knee extension, the prosthetic foot can touch the ground during swing phase of the prosthetic side, creating a risk of fall. From the literature, every people with transfemoral amputation has a falling incidence of once a year (Frossard et al., 2010) and more than half of lower limb amputee people are afraid of falling or are regularly falling (Miller et al., 2001).

To take comfort during prosthetic limb swing phase, people with transfemoral amputation resort to diverse walking strategies aiming at increasing the distance between the prosthetic foot and the ground. Gait strategies described in the literature include: the circumduction of the hip, the hip hiking strategy and the vaulting strategy (Michaud et al., 2000; Perry, 1992; Smith et al., 2004). The latter was described by Smith et al. (2004) as the "premature midstance plantar flexion by the sound limb" which "assists toe clearance of the prosthetic limb by lifting the body". Until now these strategies were mainly observed and described during locomotion of people with transfemoral amputation on flat surfaces.

* Correspondence to: C. Villa, 47 rue de l'échat, CS 20045, 94048 Creteil Cedex, France.
** Correspondence to: H. Pillet, Arts et Métiers ParisTech — Institut de Biomécanique Humaine Georges Charpak, 151 Boulevard de l'Hôpital, 75013 Paris, France.
E-mail addresses: coralie.villa@invalides.fr (C. Villa), helene.pillet@ensam.eu (H. Pillet).

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Inclination and uneven surfaces increase the risks to stumble when the prosthetic limb is mobile above the ground. Surface inclination induces gait adjustments to ensure toe clearance during swing phase of gait particularly during slope ascent or for the upstream lower limb during cross-slope walking (Dixon and Pearsall, 2010; Prentice et al., 2004). As regards non-amputee gait, considered as a reference, these adaptations are observed with the modification of lower limb joints kinematics in the sagittal plane in late stance phase and swing phase (Dixon and Pearsall, 2010; Gates et al., 2012; Prentice et al., 2004; Silder et al., 2012).

Nowadays, most of patients with transfemoral amputation are fitted with prosthetic feet unable to modify the ankle dorsiflexion angle during swing phase as observed in able-bodied participants (Prentice et al., 2004). People with transtibial amputation ensure toe clearance during swing phase of the prosthetic side by increasing the residual knee and hip flexion angles during slope ascent (Fradet et al., 2010; Vickers et al., 2008), during stairs ascent (Ramstrand and Nilsson, 2009), during uneven surfaces walking (Gates et al., 2012) or during obstacle crossing (Buckley et al., 2013; Vrieling et al., 2007). For patients with transfemoral amputation, adjustments in stairs and slopes with the prosthetic knee and the residual hip during swing phase of the prosthetic side are either reduced compared to transtibial amputee people or even absent with some friction prosthetic knees (Vrieling et al., 2008), and are different depending on micro-processed knees (Bellmann et al., 2010). In (Vrieling et al.'s (2007) study, video recordings of 8 patients with transfemoral amputation crossing an obstacle with the prosthetic side showed circumduction movements of the hip combined with plantiflexion movements of the sound ankle in support just when getting over the obstacle.

Vaulting strategy is often used in this population to guarantee toe clearance of the prosthetic limb even on flat surfaces (Drevelle et al., 2014). The present study will focus on vaulting gait identification and quantification in challenging situations of daily living in individuals with transfemoral amputation. Although this strategy is considered as a deleterious gait deviation by rehabilitation staff, only one very recent study proposed to quantify it during level walking of people with transfemoral amputation (Drevelle et al., 2014). The criterion used in this study was the generated power during mid-stance at the contralateral ankle of patients with transfemoral amputation. To our knowledge, the evolution of this parameter in limiting situations of daily living has not been investigated yet in the literature for people with transfemoral amputation. In this context, the aim of the study is to quantify the evolution of the sound ankle power in single limb support during slope ascent and cross-slope walking compared to level walking in people with transfemoral amputation.

2. Methods

2.1. Subjects

The protocol was approved by the local ethics committee and written informed consent were obtained from all participants.

Seventeen subjects with transfemoral amputation (TF-Group) (age: mean 37 years SD 10 years, height: mean 174 cm SD 9 cm, body mass: mean 76 kg SD 10 kg) participated in the study. The population is presented in details in Table 1. All participants underwent clinical evaluation to check for pain or any gait problems before recruitment. Prostheses alignment was adjusted according to the author's expertise. Seventeen able-bodied participants (age: mean 42 years SD 19 years, height: mean 176 cm SD 11 cm, body mass: 72 kg SD 15 kg) were recruited as a control population (CO-Group) with no vaulting strategy.

2.2. Protocol

All subjects followed the same protocol. Subjects were equipped with a set of 54 reflective markers placed on landmarks of the whole body (Pillet et al., 2014). 3D position of these markers during motion was captured with an optoelectronic system (Vicon 8i, 100 Hz, Oxford Metrics, Oxford, UK). Subjects walked at a comfortable self-selected speed on a flat surface (level walking), on a cross-slope device inclined of 10%, on a 5% inclined slope device (gentle slope) and on a 12% inclined slope device (steep slope). All walking devices were instrumented with two force platforms (AMTI, 100 Hz, Watertown, MA, USA). Gait analysis data obtained for level walking, slope ascent and cross-slope walking with the prosthetic limb upstream were used in the study. At least three valid trials were recorded. A trial was considered successful when each lower limb of the participant was in full contact with each force platform.

2.3. Data processing

A 13 segment model was created (foots, shanks, thighs, pelvis, trunk, head, arms, lower-arms). Anatomical frames were defined for each segment of the model (Pillet et al., 2014). Spatiotemporal parameters and lower limb joint kinematics and kinetics in the frontal, transverse and sagittal planes were computed as described in Pillet et al. (2014) in each walking situation (flat surface, downstream on cross-slopes, gentle slope ascent, and steep slope ascent). Particularly, ankle power in the sagittal plane was defined as the product of ankle moment and ankle angular velocity in the sagittal plane, and normalized by body mass. Ankle power in the sagittal plane was computed for participants with

Table 1
Characteristics of the participants with transfemoral amputation.

Patient	Amputation				Fitting		
	Side	Cause	Stump length (cm)	Time (years)	Socket	Prosthetic knee	Prosthetic foot
TF01	L	Trauma	34	20	Ischial containment	C-Leg® (Ottobock)	1C40 C-Walk® (Ottobock)
TF02	R	Trauma	31	2	Ischial containment	C-Leg® (Ottobock)	Highlander® (Freedom)
TF03	L	Trauma	19	16	Ischial containment	C-Leg® (Ottobock)	1C40 C-Walk® (Ottobock)
TF04	R	Trauma	46	21	Knee-disarticulation prosthesisEnd-weight-bearing	C-Leg® (Ottobock)	Flex walk® (Ossur)
TF05	L	Trauma	37	16	Ischial containment	C-Leg® (Ottobock)	1C60 Triton® (Ottobock)
TF06	R	Tumour	41	1	Knee-disarticulation prosthesisEnd-weight-bearing	C-Leg® (Ottobock)	Flex walk® (Ossur)
TF07	R	Trauma	48	3	Knee-disarticulation prosthesisEnd-weight-bearing	OH5® (Medi)	ERF® foot + Multiflex® ankle (Endolite)
TF08	L	Trauma	38	2	Ischial containment	Sensor® (Nabtesco)	Variflex® (Ossur)
TF09	R	Trauma	46	2	Knee-disarticulation prosthesisEnd-weight-bearing	KX06® (Endolite)	1C60 Triton® (Ottobock)
TF10	L	Trauma	36	–	Ischial containment	C-Leg® (Ottobock)	Flex walk® (Ossur)
TF11	L	Trauma	31	–	Ischial containment	C-Leg® (Ottobock)	Flex walk® (Ossur)
TF12	L	Trauma	27	3	Ischial containment	C-Leg® (Ottobock)	Flex walk® (Ossur)
TF13	L	Trauma	27	34	Marlo Anatomical Socket (MAS®)	RheoKnee® (Ossur)	Reflex Shock® (Ossur)
TF14	L	Trauma	34	5	Ischial containment	Hybrid Knee® (Nabtesco)	Variflex® (Ossur)
TF15	L	Trauma	26	15	Marlo Anatomical Socket (MAS®)	RheoKnee® (Ossur)	Reflex Rotate® (Ossur)
TF16	L	Trauma	34	4	Marlo Anatomical Socket (MAS®)	Genium® (Ottobock)	Elation® (Ossur)
TF17	L	Trauma	36	16	Ischial containment	Hybrid Knee®(Nabtesco)	Flex walk® (Ossur)

transfemoral amputation at the contralateral ankle over the contralateral lower limb gait cycle, and for able-bodied participants at the left lower limb over the left lower limb gait cycle. For each trial of each participant, the peak of ankle power in the sagittal plane was quantified during single limb support. This parameter was called FlexPwr and expressed in W/kg. A negative value of FlexPwr indicates a maximum of absorbed power at the sound ankle and a positive value of FlexPwr indicates a maximum of generated power at the sound ankle during single limb support in stance phase.

For the control population (CO-Group), mean and standard deviation of the parameter FlexPwr were then computed over all trials of all able-bodied participants in each walking situation.

In Drevelle et al. (2014), the same participants with transfemoral amputation were screened for vaulting strategy during level walking (flat surface situation). For all the participants clinically identified with vaulting gait during level walking, FlexPwr was higher than 0.15 W/kg (Drevelle et al., 2014). In addition, Silder et al. (2012) and Fradet et al. (2010) showed in two groups of 16 able-bodied participants that ankle power in the sagittal plane during single support remained below this value when climbing 5%, 10% and 12% (7.5°) inclined slopes. This value was used as a threshold and called "vaulting threshold" across the paper. To detect any peak of generated power at the sound ankle in mid-stance, the value of FlexPwr computed in each trial for each participant with amputation was compared to this minimal value (0.15 W/kg) in all walking situations in TF-Group.

Secondly, for patients with FlexPwr above the vaulting threshold for all trials while walking on flat surface (FV-Group), the evolution of the abnormal generated power by the sound ankle between level walking and the other walking situations was investigated. Variations of the parameter FlexPwr between the flat surface situation and all other walking situations were computed. The variation is computed as the difference between the mean value of the parameter in a limiting situation (slopes or cross-slopes) and the mean value of the parameter obtained on flat surface. These variations are computed for each patient and averaged among the FV-Group.

2.4. Statistics

The effect of the "walking situation" was tested on gait velocity and FlexPwr in CO-Group, on gait velocity in TF-Group and on FlexPwr in FV-Group, using a non-parametric Wilcoxon test for two paired samples among situations (flat surface/cross-slopes, flat surface/gentle slope, flat surface/steep slope). In order to investigate the effect of the walking situations on the variation (increase) of the parameter FlexPwr between level walking and each other walking situation, a non-parametric Wilcoxon test for two paired samples was performed on the variation of the parameter FlexPwr between situations. For both statistical tests, when the null hypothesis was rejected, a significant difference among situations was considered for the parameter of the population with a probability of $P < 0.05$ indicated as high when $P < 0.001$.

3. Results

3.1. Gait velocity

Average gait velocity and standard deviation obtained for TF-Group and CO-Group in each walking situation are presented in Table 2. Gait velocity in TF-Group is of same order of magnitude as in CO-Group during level walking, cross-slope walking and gentle slope ascent. The gait velocity was much lower for people with amputation compared to controls during steep slope ascent.

3.2. CO-Group: Averaged FlexPwr for each walking situation

Fig. 1 (left part) shows mean curves of the ankle flexion power obtained in CO-Group during level walking, cross-slope walking, gentle slope ascent and steep slope ascent. Table 3 presents mean parameter (FlexPwr) computed in CO-Group in all four walking situations. The statistical analysis highlighted that the parameter FlexPwr significantly increased between level walking and slope ascent by about 0.07 W/kg for gentle slope and 0.27 W/kg for steep slope but remained far below 0.15 W/kg.

Table 2
Gait velocity (m/s) of participants with transfemoral amputation (TF-Group) and control subjects (CO-Group) in each walking situation. Mean value, standard deviation (SD) and range [min; max] are given for each group.

	TF-Group gait velocity (m/s)			CO-Group gait velocity (m/s)		
	Mean	SD	Range	Mean	SD	Range
Flat surface	1.27	0.13	[0.97; 1.46]	1.32	0.12	[1.02; 1.52]
Cross-slopes	1.14	0.17	[0.85; 1.38]	1.15	0.15	[0.82; 1.49]
Gentle slope (ascent)	1.19	0.15	[0.99; 1.41]	1.20	0.12	[0.83; 1.48]
Steep slope (ascent)	1.09	0.14	[0.80; 1.41]	1.19	0.16	[0.83; 1.53]

3.3. TF-Group: FlexPwr for each participant with transfemoral amputation in each walking situation

Table 4 presents, for each patient, the parameter FlexPwr averaged over all trials while walking on a flat surface, on cross-slopes with the prosthetic limb upstream and while sloping gently and steeply upwards. Three to seven trials were analysed per situation per patient. In five particular cases, experimental issues prevented from computing FlexPwr for at least three trials (missing data in Table 4). When FlexPwr exceeded the vaulting threshold, the trial was classified as vaulting trials. The percentage of vaulting trials for each participant with amputation could then be computed.

According to Table 4, the vaulting threshold was overstepped (FlexPwr > 0.15 W/kg) in all walking trials for eight patients out of seventeen (47%) during level walking, for eight patients out of fifteen (53%) during cross-slope walking with the prosthetic limb upstream and for ten patients out of fifteen (67%) during gentle slope ascent. While walking uphill of the steep slope, ten patients out of sixteen (63%) showed a maximum of generated power at the contralateral ankle above the vaulting threshold in all recorded trials. In Table 4, for five patients (TF04, TF05, TF07, TF08, TF16), curves of the contralateral ankle power in the sagittal plane were not repeatable across trials. Particularly, for TF04, TF05 and TF16, the vaulting threshold, which never exceeded on flat surface, cross-slopes and gentle slopes, was irregularly overstepped during steep slope ascent. Irregular values above vaulting threshold were also observed for TF08 in almost all situations and TF07 on cross-slopes. Finally, only two patients (TF06 and TF11) did not exceed the vaulting threshold in all walking situations.

3.4. FV-Group: Variation of FlexPwr between level walking and the other walking situations

Patients included in the FV-Group had 100% of trials on flat surface with FlexPwr exceeding the vaulting threshold (Table 3). All patients in the FV-Group (TF01, 02, 03, 12, 13, 14, 15, 17) also showed, during single support of their contralateral ankle, a maximum generated power above the vaulting threshold in all trials in the other walking situations. Fig. 1 (right part) displays mean sound ankle power curves in all walking situations obtained by averaging results of the eight patients in FV-Group. Table 5 shows the averaged variations of FlexPwr between flat surface and the other walking situations for all patients in FV-Group.

In this group of patients, FlexPwr significantly increases between level walking and cross-slope walking, gentle slope ascent and steep slope ascent ($P < 0.05$). In addition, the mean variation of the maximum generated sound ankle flexion power was significantly higher during steep slope ascent than during gentle slope ascent and cross-slope walking ($P = 0.03 < 0.05$).

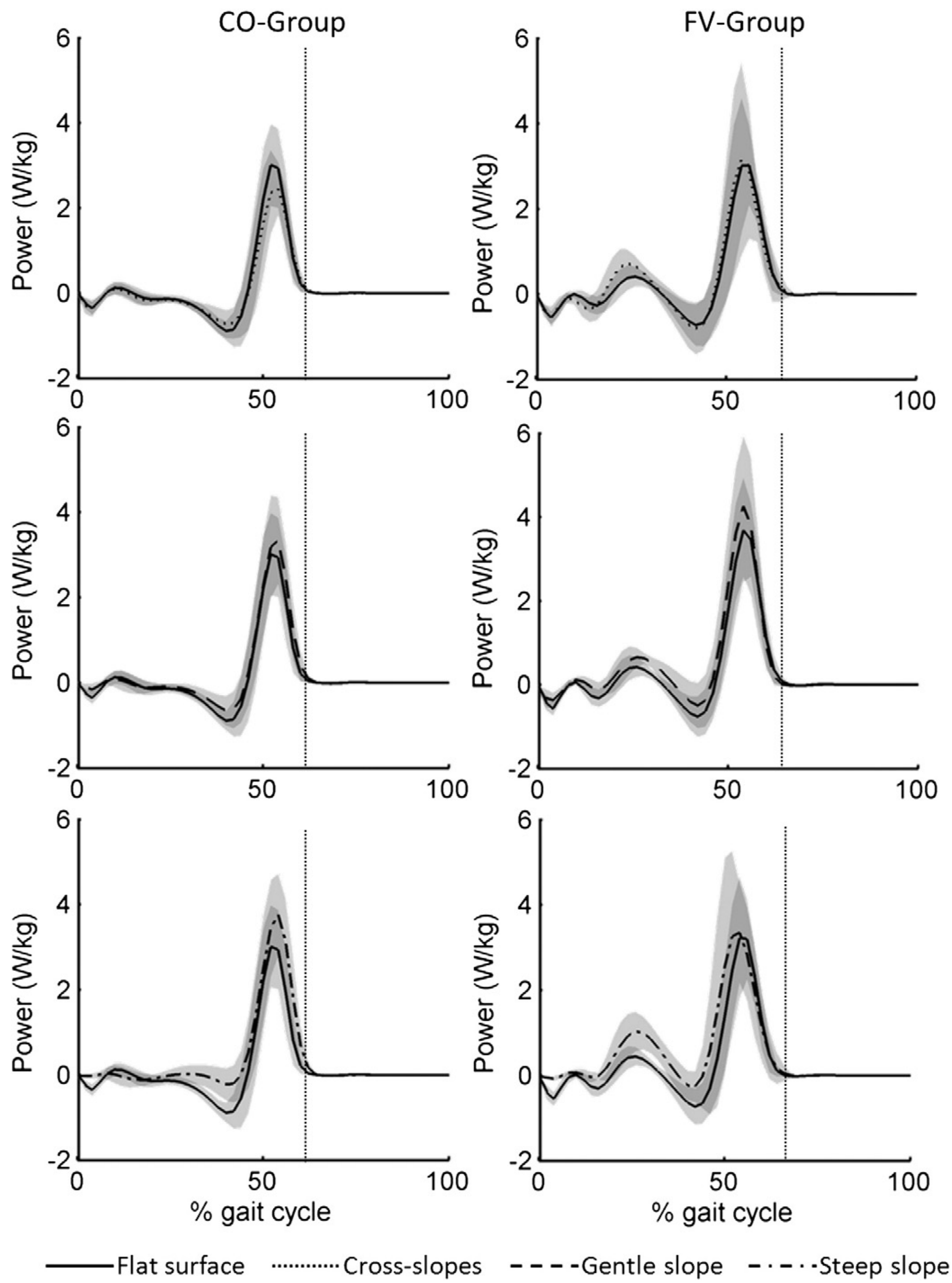

Fig. 1. Ankle flexion power (W/kg) as the percentage of gait cycle (%). Mean curves and corridors (one standard deviation) obtained at the left ankle during left limb gait cycle in CO-group (left part) and at the controlateral ankle during controlateral limb gait cycle in FV-Group (right part) in all walking situations: flat surface (solid line), cross-slopes (dotted line), gentle slope (dashed line), steep slope (dash-dotted line).

Table 3
Mean and standard deviation values of the parameter FlexPwr (W/kg) for control subjects (CO-Group) in the four walking situations. A significant difference compared to level walking is indicated with * for $P < 0.05$ and ** for $P < 0.001$.

	CO-Group	
	FlexPwr (W/kg)	
	Mean	SD
Flat surface	−0.24	0.12
Cross-slopes (downstream)	−0.26	0.09
Gentle slope (ascent)	−0.17*	0.13
Steep slope (ascent)	0.03**	0.20

Table 4
Mean and standard deviation (SD) values of FlexPwr parameter of each patient over all trials in each situation for contralateral limb in TF-Group. The percentage of trials (%) in each situation for which FlexPwr value was above vaulting threshold is given for each patient. When differing from 0% and 100% the number of trials above vaulting threshold are indicated out of the number of valid trials in the situation. "–" = missing data.

	Flat surface			Cross-slopes (downstream)			Gentle slope (ascent)			Steep slope (ascent)		
	Mean	SD	%	Mean	SD	%	Mean	SD	%	Mean	SD	%
TF01	0.50	0.08	100%	–	–	–	0.71	0.06	100%	1.63	0.23	100%
TF02	0.63	0.04	100%	–	–	–	0.81	0.31	100%	1.40	0.25	100%
TF03	0.43	0.14	100%	0.48	0.04	100%	–	–	–	0.58	0.10	100%
TF04	−0.41	0.03	0%	−0.60	0.08	0%	−0.27	0.04	100%	0.50	0.68	40% (2/5)
TF05	−0.07	0.03	0%	−0.21	0.17	0%	−0.01	0.03	0%	0.13	0.17	25% (1/4)
TF06	−0.02	0.00	0%	−0.08	0.01	0%	−0.08	0.02	0%	−0.03	0.02	0%
TF07	−0.05	0.04	0%	0.02	0.07	20% (1/5)	0.2	0.04	100%	–	–	–
TF08	0.15	0.17	33% (1/3)	0.31	0.31	50% (2/4)	0.55	0.23	100%	0.34	0.20	60% (3/5)
TF09	−0.15	0.08	0%	0.26	0.08	100%	0.45	0.15	100%	1.54	0.19	100%
TF10	0.04	0.01	0%	0.31	0.1	100%	0.02	0.05	0%	0.55	0.05	100%
TF11	0.07	0.05	0%	0.05	0.07	0%	0.00	0.01	0%	0.03	0.02	0%
TF12	0.32	0.12	100%	0.63	0.14	100%	0.44	0.2	100%	1.46	0.4	100%
TF13	0.66	0.08	100%	1.03	0.07	100%	–	–	–	1.23	0.17	100%
TF14	0.37	0.09	100%	0.78	0.08	100%	0.82	0.15	100%	0.96	0.23	100%
TF15	0.81	0.18	100%	0.89	0.15	100%	1.02	0.12	100%	1.32	0.41	100%
TF16	−0.06	0.02	0%	−0.17	0.05	0%	−0.1	0.12	0%	0.35	0.36	60% (3/5)
TF17	0.35	0.14	100%	0.66	0.17	100%	0.62	0.31	100%	1.04	0.23	100%

4. Discussion

The study aims at quantifying the evolution of flexion power generation by the contralateral ankle during its single limb support, for several limiting situations of daily living during gait of people with transfemoral amputation.

During normal walking on flat surface, a sound ankle joint absorbs power during stance phase of gait (Perry, 1992). This absorbed power is subsequent to the eccentrical work of the triceps when stretched as the shank is moving forward (Perry, 1992). The absorbed ankle joint power was actually observed in the control population of this study during level walking, and also during cross-slope walking and gentle slope (5%) climbing. During ascent of the steep slope, on the contrary a low generated power (mean 0.03 W/kg, SD 0.20 W/kg) was observed at the ankle in the control group during single limb support. This finding is consistent with the curves drawn by Fradet et al. (2010) representing ankle flexion power of sixteen able-bodied participants walking uphill on a slope of 7.5° (12%) of inclination. These results highlighted the necessity to generate power at the ankle from the single limb support in this walking situation, which should contribute to rise the centre of gravity.

In patients with transfemoral amputation, the ankle power curve at the contralateral side during single support of the controlateral limb was different between patients. Some patients showed a generated power by the sound ankle at mid-stance above 0.15 W/kg. This generated power was shown to be a criterion of vaulting clinical gait strategy for this population during level walking (Drevelle et al., 2014). Results in CO-Group highlighted that ankle power remained on average below this value in all walking situations, in agreement with Fradet et al. (2010) and Silder et al. (2012). Consequently, a peak of generated ankle power in the sagittal plane at mid-stance above the threshold value in cross-slopes and slope ascent should traduce vaulting gait strategy. From the results, the number of patients affected and the evolution of vaulting quantity can be discussed.

Table 5
Mean variation of FlexPwr between level walking (flat surface) and other walking situations in FV-Group. The second column of the table shows as an interpretation the relative variation compared to the value of the maximum generated power measured for level walking.

	Variation of FlexPwr (in W/kg) compared to flat surface			Increase of FlexPwr (in %) compared to flat surface		
	Mean	SD	Range	Mean	SD	Range
Cross-slopes (downstream)	0.26	0.15	[0.05; 0.41]	62%	44%	[10; 111]
Gentle slope (ascent)	0.24	0.11	[0.12; 0.45]	33%	13%	[21; 55]
Steep slope (ascent)	0.71	0.33	[0.15; 1.14]	158%	103%	[35; 356]

The method revealed that the number of patients with vaulting gait increases in slopes and cross-slopes compared to level walking. In particular, 88% of recruited patients were at least once generating flexion power at the contralateral ankle during steep slope ascent. These results highlight the necessity to take into account vaulting gait in ecological situations as most of people with transfemoral amputation resort to this strategy when walking in their daily living environment.

Moreover, patients in the FV-Group, demonstrated an increase of the maximum of generated sound ankle flexion power between level walking situation and the limiting walking situations. The estimated increase for steep slope ascent (mean 0.68 W/kg, SD 0.39 W/kg) was significantly higher than for gentle slope ascent (mean 0.29 W/kg, SD 0.16 W/kg) and significantly higher than for cross-slope walking (mean 0.33 W/kg, SD 0.15 W/kg). These variations suggest that patients adjust sound ankle power generation according to the difficulty of the situations. In the specific case of the steep slope (12%), the power production can participate to the propulsion essential for ascension, like observed in able-bodied participants.

However, walking uphill of the 12%-inclined slope appeared to be the most limiting situation for several reasons. First of all, gait speed decreased compared to level walking in all situations in amputee and non-amputee groups of subjects. For patients with transfemoral amputation, gait speed reduction was comparable to the one observed in control subjects during locomotion on the cross-slope device and the gentle slope (Table 1), while it was more important during locomotion on the steep slope. This result is consistent with the decrease of gait speed observed for people with transtibial amputation in the same situation (Langlois et al., 2014). Additionally, for three patients, an abnormal generated ankle power was irregularly observed during steep slope ascent. But these patients did not use vaulting gait in the other walking situations. Then, it seems that this gait strategy could be used to cross this particular situation. In addition, two other participants with transfemoral amputation already showed irregular patterns during cross-slope walking. In steep slope ascent, they either kept an irregular use of vaulting gait or adopted it in all trials.

Finally, only two patients did not show any generated power values higher than 0.15 W/kg in all tested walking situations. However, during steep slope ascent, other compensatory strategies described in the literature like hip circumduction, and hip hiking, sometimes even combined with an amplified trunk homolateral inclination, were clinically observed (Starholm et al., 2010). Participants with amputation without generated ankle power in midstance or irregular sound ankle power patterns were assumed to use other strategies to help for toe clearance in this difficult situation. Qualitative video analysis did not reveal any hip circumduction or amplified trunk homolateral inclination on the population. More participants need to be recruited to investigate and quantify in future work hip hiking strategy in slopes and cross-slopes.

Finally, the results showed that analysing the gait on steep slope in a clinical environment could be an interesting way to exacerbate vaulting gait to evaluate the risk that patients use this deleterious strategy in real life conditions. In the same way, it could be used as a training situation during rehabilitation.

Although this study provides a useful tool for clinical evaluation of people with transfemoral amputation vaulting gait, fatigue was not properly taken into account in the study. Indeed participants were recorded on a limited amount of trials to obtain data in the different situations. Moreover, vaulting threshold could be refined using gait speed and maximum of generated ankle power during propulsion, before use in clinical routine. In addition, relationship of vaulting gait with prosthetic fitting was not investigated. Participants were fitted however with similar types of prosthetic components.

5. Conclusions

This study is the first one evaluating the evolution of one specific gait deviation between several daily living situations of locomotion. The vaulting strategy is currently only identified in clinical practice using visual criteria. Quantification with a power parameter allowed to estimate the vaulting quantity. Results showed that the vaulting strategy is widely used by people with transfemoral amputation to secure prosthetic limb swing phase ensuring toe clearance. It appeared that the more difficult the situation is, the higher the number of patients using this compensatory strategy. Indeed, on the one hand all patients with transfemoral amputation using vaulting during level walking used it in more limiting situations, and on the other hand, even if some patients did not have recourse to the strategy on flat surfaces, they could use it in limiting situations. Moreover, the study highlighted that patients were able to dose out the quantity of vaulting according to the difficulty of the situation relative to toe clearance of the prosthetic limb. Therefore the vaulting strategy revealed itself as a gait pattern (conscious or unconscious depending on the patients) that contributed to the adaptation in limiting situations to help for toe clearance. However, as the vaulting strategy could be deleterious for people with transfemoral amputation, this study supports the importance to take it into account in the rehabilitation process of the patients, particularly in limiting situations, which are integral part of daily living.

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