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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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ABSTRACT

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. Kinematic 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 situations. 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.

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* 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.

	Amputation				Fitting		
Patient	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)