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Knee and hip internal moments and upper-body kinematics in the frontal plane in unilateral transtibial amputees

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Objective: The aim of this study was to quantify the motor adaptations in the frontal plane made by unilateral transtibial amputees (UTAs), with special regard to: (1) abduction/adduction moment at the hip and knee valgus moment in the frontal plane; (2) pelvic and thorax obliquity; and (3) stride length and gait speed.

Methods: 15 Males with unilateral transtibial amputation comprised the subject group and 15 non-disabled individuals served as control group. Gait analysis was performed using the VICON MOTION SYSTEM® (Oxford Metrics, Oxford, UK).

Results: In this study, UTAs walked with a reduced hip abductor moment during the stance phase. At the knee joint, the valgus moment was reduced in the prosthetic limb compared to the sound and the control limb. The thorax range of motion in the frontal plane was increased on the prosthetic side, compared with the non amputee subjects.

Conclusion: Our findings suggest that unilateral transtibial amputation patients walk with different motor control strategies in the frontal plane compared with the non-disabled subjects. These results suggest the need for specific training for this group of UTAs, focusing on exercises to stabilize and strengthen the proximal muscles as well as practicing balance and coordination in the coronal plane.

1. Introduction

Amputation is regarded as a disabling health problem. The overall incidence of amputation varies widely across countries. Transtibial amputation rate in the United States has consistently remained between 9 and 12.5 per 100,000 population since 1990 [1–3].

The major structural asymmetry arising from the amputation results in loss of muscle and sensory feedback. Nonetheless, after a period of rehabilitation and application of a functional prosthesis, lower extremity amputatees can walk and run, and appear to do so with reasonable temporal and kinematic symmetry [4,5]. However, kinematic symmetry is achieved by substantial neuromuscular asymmetry because the missing tissues present an additional challenge to the motor control system [5]. Numerous biomechanical studies have assessed walking patterns after amputation [6–14].

Several motor control strategies have been described by different authors in the sagittal plane during the gait of unilateral transtibial amputees gait [5,6,8–10]. Although the sagittal plane kinetics of the knee and hip have been well documented, the effects of unilateral transtibial amputation on the knee and hip joint kinetics in the frontal plane, have not been sufficiently investigated.

Human walking requires the coordination and movement of both limbs in all three planes [15]. Several authors have shown that the hip abduction moment can help to maintain body balance while others have found that hip movements in both frontal and transverse planes can contribute to the total work generated during steady-state walking [12,16,17].

It is possible that, because of their focus on the sagittal plane joint kinetics, previous studies have only explained a small part of the adaptations that occur due to unilateral transtibial amputation during gait. The aim of this study was to quantify the motor adaptations in the frontal plane made by unilateral transtibial amputees (UTAs), with special regard to: (1) pelvic and thorax obliquity; (2) abduction/adduction moment of the hip and knee valgus moment in the frontal plane; and (3) stride length and gait. It was hypothesized that UTAs would demonstrate frontal plane kinetic differences in the proximal joints on both the prosthetic and sound limbs compared to able-bodied individuals.

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Table 1
Subjects characteristics.

	UTAs group ($n = 15$)		Control group ($n = 15$)
Age[↔]	56.33 (14.15)[*]		47.6 (14.05)
Weight (kg)[↔]	77.37 (14.19)[*]		70.72 (9.35)
Height (cm)[↔]	175.57 (9.64)[*]		171 (7.56)
	Prosthetic limb	*Sound limb*	
Leg length[±]	87.84 (5.82)[*,+]	87.91 (1.23)[*]	90.32 (5.44)

UTAs, unilateral transtibial amputees. Values are mean and standard deviation (S.D).
[*] $p > 0.05$ vs. control group.
[+] $p > 0.05$ vs. sound limb.
[↔] Student's t-test.
[±] Analysis of variance (ANOVA) with a single factor and Bonferroni adjustment a posteriori tests.

2. Materials and methods

2.1. Participants.

The study was approved by the Human Ethics Committee, and informed consent was obtained from all participants. 15 Males with UTAs comprised the subject group and 15 non-disabled individuals served as control group. The control group was matching the UTAs group in age, weight and height (Table 1). All subjects were able to walk independently and did not use any assistive device. The patients had been using their own prosthesis for more than one year before being included in the study.

Prosthetic alignment was established clinically, with each fitting being assessed and optimized by a team of two certified prosthetists. All participants were considered stable in their prosthetic adjustment. The prosthesis alignment method based on different reference points and axes was developed at Strathclyde University in 1975 by Radcliffe and Foort, and has not changed substantially since then. In general terms, it is accepted that, in a tibial prosthesis, the socket should support 5° flexion and approximately 5° of valgus in the frontal plane [18]. For optimal function [19], the feet were aligned in slight plantar flexion.

Exclusion criteria included the use of any walking assistive device, stump pain or tenderness and any cardiovascular, neurological or musculoskeletal abnormality influencing gait.

Table 2 shows the characteristics of the prosthesis.

2.2. Experimental protocol

Gait analysis was performed using the VICON MOTION SYSTEM® (Oxford Metrics, Oxford, UK). This system was a three-dimensional motion analysis system consisting of eight 100 Hz cameras with infrared strobes, two AMTI® force-plates (Watertown, USA) and a data-station where the information was gathered and processed by VICON Plug-in Gait 2.0® [20].

Special lightweight surface markers (23) were attached directly to the skin or the prosthesis and placed over standardized landmarks on the sound limb, residual limb and trunk or corresponding spots on the prosthesis (C7 vertebra, T10 vertebra, left and right acromion, right scapula, jugular notch (where the clavicle meets the sternum), sternum, anterior and posterior superior iliac spines (left and right), lateral thigh, lateral femoral condyle, lateral leg, lateral malleoli, second metatarsal head and the posterior heel) according to the biomechanical model of Kadaba et al. and Davis et al. [21,22]. On the prosthesis, the knee marker was placed over the joint center and the ankle marker was attached to the point corresponding to the lateral malleolus on the intact side.

The patients and controls were instructed to walk along the 8 m walkway while wearing their usual shoes. The participants were asked to walk at a self-selected comfortable speed. A successful trial was one in which the foot of interest landed fully on the force plate.

Table 2
Lower extremity amputee and prosthesis characteristics.

UTAs	Etiology	Lower extremity amputee	Prosthetic foot	Socket
1	Traumatic	Right	Single-axis foot	TSB
2	Traumatic	Right	CeterusFoot®	TSB
3	Traumatic	Left	FlexFoot®	TSB
4	Tumoral	Left	FlexFoot®	TSB
5	Traumatic	Right	CeterusFoot®	TSB
6	Traumatic	Left	QuantumFoot®	TSB
7	Traumatic	Right	FlexFoot®	TSB
8	Traumatic	Right	FlexFoot®	TSB
9	Traumatic	Right	VariFlex®	TSB
10	Traumatic	Right	FlexFoot®	TSB
11	Traumatic	Right	Talux®	TSB
12	Traumatic	Left	VariFlex®	TSB
13	Tumoral	Right	Triasfoot®	TSB
14	Tumoral	Right	FlexFoot®	TSB
15	Traumatic	Left	FlexFoot®	TSB

UTAs, unilateral transtibial amputees; TSB, total surface bearing.

2.3. Data analysis

We analyzed the internal joint moments of the hip and knee in the frontal plane. The following kinetic parameters were analyzed: first and second peaks of the hip abductor moment, first and second peaks of the knee valgus moment. Additionally, we analyzed walking speed and stride length, and the range of movement (ROM) of the pelvis and thorax in the frontal plane.

The VICON plug in gait model 2.0® was used to calculate outcome measures [20]. The output angles for all joints were calculated from the YXZ cardan angles derived by comparing the relative orientations of the two segments. Pelvis and thorax markers were measured relative to the laboratory axes. The position of all other segments was measured relative to the proximal segment e.g. femur to the pelvis [20].

Even thought the pelvis and thorax are rigid segments, their movements have been separated into movements of the prosthetic side and the sound side in this article.

Joint internal moment calculations were determined from synchronized co-ordinate and force data using an inverse dynamics approach [16,23]. Joint kinetics were normalized to body weight, and all parameters were normalized to 100% of the gait cycle.

The control group was measured with the same procedure for left and right leg. As no significant discrepancy was found, mean values for left and right leg together were used in the calculations.

2.4. Statistical analysis

Statistical analysis was performed using SPSS 17.0. Shapiro and Wilk's W-statistic was used to screen all data for normality of distribution. The subjects were height/weight matched. Single-factor analysis of variance (ANOVA) and Bonferroni adjustment a posteriori tests were used to compare the sound, prosthetic and control limbs. Walking speed comparisons between the controls and UTAs were determined using Student's t-test. A significance level of 0.05 was used for all statistical comparisons.

3. Results

A total of 15 subjects with unilateral transtibial amputation and 15 controls were enrolled in the study. The groups did not differ in age, height, weight and length of the lower extremities. The controls and UTAs walked at a similar velocity and with similar stride length (Table 3).

3.1. Pelvis and thorax obliquity in the frontal plane

In the frontal plane, negative (down) pelvic obliquity value relates to the situation in which the opposite side of the pelvis is lower [20]. In this study, there were no significant differences between the prosthetic and sound sides and the control group. A positive (up) thorax obliquity angle relates to the situation in

Table 3
Spatio-temporal parameters.

	UTAs group ($n = 15$)		Control group ($n = 15$)
Walking speed (m/s)[↔]	1.19 (0.16)[*]		1.24 (0.16)
	Prosthetic limb	*Sound limb*	
Stride length (m)[±]	1.36 (0.13)[*,+]	1.27 (0.18)[*]	1.34 (0.12)

UTAs, unilateral transtibial amputees. Values are mean and standard deviation (S.D).
[*] $p > 0.05$ vs. control group.
[+] $p > 0.05$ vs. sound limb.
[↔] Student's t-test.
[±] Analysis of variance (ANOVA) with a single factor and Bonferroni adjustment a posteriori tests.