An in-shoe device for assessment of gait abnormalities: three case studies

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***Abstract*—The asymmetrical gait patterns of lower-limb amputees have been reported in many studies. Such asymmetry has been recognized as the cause of many side-effects (e.g. joint degeneration, osteoarthritis in the residual limb, osteoporosis in the intact limb) deriving from the high overloading of the sound limb. The present study is aimed at investigating amputees' gait abnormalities through a couple of pressure-sensitive insoles; the device allows the collection of a large number of steps in an ecological fashion. Results about gait performance are in line with those reported in literature, confirming that the system is suitable to recognize gait abnormalities that can be relevant for clinical diagnosis.**

***Keywords*—Wearable sensors, sensorized insoles, gait analysis, lower-limb amputees.**

I. Introduction

GAIT abnormalities of unilateral lower-limb amputees have been studied by many authors [1-2]. Most of these studies have shown the asymmetric gait patterns of transtibial [3] and transfemoral [4] amputees. Generally, lower-limb amputees have a longer stance phase on their intact limb compared to the prosthetic limb [4]; they also load the intact limb more than the prosthetic limb. As a consequence of the overloading of the intact limb, amputees are more prone to pain on the intact limb, joint degeneration, and osteoarthritis than able-bodied subjects [5].

Various methods have been adopted to quantify the human gait of people with gait abnormalities; in this field, motion analysis systems and force platforms represent the gold standards [6]. Wearable devices represent an emergent method to optimize the recording of a large number of steps with people unable to walk for prolonged experimental sessions [7]. These systems also allow to acquire ecological measurements in every-day environment. Among wearable devices, pressure-sensitive insoles allow the study of the dynamic interaction between the foot (i.e. normal or pathological) and the shoes, avoiding the targeting effects that usually affects force-platform measurements [8].

The aim of this study is to investigate gait abnormalities of three lower-limb amputees through a couple of pressure-sensitive insoles. Data were used to extract some temporal gait parameters, a symmetry index and the vertical ground reaction force profiles. Results are reported and discussed through the comparison with the reference data reported in previous studies.

II. Matherials and Methods

A. Subjects and Protocol

Three lower-limb amputees participated in the study. Subject #1 and Subject #2 are amputated at transfemoral level; Subject #3 has a transtibial amputation. All subjects underwent amputation following a trauma and were not affected by any pathology. Subjects were allowed to use walking aids (i.e. one or two crutches) during the experiment. The main characteristics of the three subjects (i.e. age, body mass index namely BMI, amputation side, type of amputation and years since amputation) are summarized in Table I.

The subjects have also been selected because of their similar shoe size (41-43 EU), in order to be comfortable when wearing the instrumented shoes. It is a worth noting that the equipment did not hinder the movements of the subjects during walking.

Subjects were asked to walk on straight line along a 30m-long corridor, at preferred self-selected speed, for 3 minutes.

Figure 1 represents one of the three subjects in the experimental environment.

B. Measurement system

Two pressure-sensitive insoles were inserted in the shoes in place of regular insoles. This device has been fully described in [8] and has already been used for gait segmentation purposes [9]; it was also proposed as part of a system for providing amputees with an augmenting feedback [10]. The insole is made of an array of 64 optoelectronic pressure sensors, covered by silicone shells [11]. The sensor array measures the pressure over the plantar area, with the exception of the plantar arch (notably, this area is not stressed during gait). The onboard electronics (placed laterally on the shoe) samples the signals at 100 Hz frequency and transmits the data, wirelessly, to a remote data logging computer.

C. Data analysis

Signals from pressure-sensitive insoles were collected and

TABLE I
SUBJECT'S CHARACTERISTICS

Subject	*Age*	*BMI*	*Amputation Side*	*Type of amputation*	*Years since amputation*
Subject 1	53	28	Left	Transfemoral	3
Subject 2	66	23	Right	Transfemoral	4
Subject 3	41	24	Left	Transtibial	11

TABLE II
TEMPORAL GAIT PARAMETERS

Subject	*Stance L [s]*	*Stance R [s]*	*Swing L [s]*	*Swing R [s]*	*Double Support L [s]*	*Double Support R [s]*	*Cadence [Hz]*	*SI*
Subject 1	1.63 ± 0.09	1.95 ± 0.13	1.04 ± 0.06	0.73 ± 0.05	0.48 ± 0.04	0.42 ± 0.10	0.38 ± 0.01	0.84 ± 0.06
Subject 2	1.21 ± 0.04	0.98 ± 0.04	0.59 ± 0.04	0.84 ± 0.03	0.11 ± 0.01	0.26 ± 0.05	0.55 ± 0.02	0.81 ± 0.04
Subject 3	0.78 ± 0.05	0.76 ± 0.05	0.47 ± 0.03	0.49 ± 0.04	0.14 ± 0.01	0.15 ± 0.03	0.80 ± 0.05	1.03 ± 0.05

processed offline in order to extract relevant temporal gait parameters. The 64 voltage signals were used to compute the values of the ground reaction force (*vGRF*) and the longitudinal position of the center of pressure (*CoPy*). A threshold of 20 N was set to identify the stance from the swing phase. For each step the duration of the stance, swing, double support and cadence was calculated (the algorithm for the extraction of gait parameters is described in [8]). Moreover, a symmetry index was calculated as the ratio of the stance time of the prosthetic leg over the one of the sound leg.

Results of the temporal parameters and symmetry index are reported in Table II. We also reported in Figure 2 the average vGRF profile of left and right feet of each subject.

III. RESULTS AND DISCUSSION

Results of the stance duration, for the two transfemoral amputees (i.e. Subject #1 and Subject #2), reveal a much longer duration of the weight support on the sound limb than on the prosthetic limb; in both subjects, the high difference between the average left and right stance durations explains the resulting low symmetry index (Subject #1, SI: 0.84 ± 0.06; Subject #2, SI: 0.81 ± 0.04). The values of the symmetry indexes are fully in line with those reported in previous works that investigated the gait symmetry of transfemoral amputees (generally the SI of lower limb amputees does not exceed 0.92) [12]. Swing phase also shows a typical asymmetrical pattern, being longer on the prosthetic limb than on the intact limb. The double support phase slightly differs, for Subject #1, between the prosthetic and sound limbs; conversely Subject #2 reveals a high asymmetry also in this parameter. The average step cadence was 0.38 ± 0.01 Hz (46 ± 1 steps/minute) for Subject #1, and 0.55 ± 0.02 Hz (66 ± 2 steps/minute) for Subject #2; these values indicate a slower walking speed if compared with able-bodied subjects. Looking at the vGRF profiles, it is noticeable that both subjects show, on the prosthetic side, a double-peak profile, with the first peak occurring at weight acceptance and the second in correspondence with the push off; on the contrary, the sound limb profiles reveal atypical shapes of the curves. Indeed, generally the sound limb is used to settle the balance, and the propulsive peak is not always present. Results for the transtibial amputee (i.e. Subject #3) depict a quite perfect symmetry of gait, with an average value of 1.03 ± 0.05; this value is fully comparable with values reported for healthy subjects [13]. Also, the average step cadence (0.80 ± 0.05 Hz, meaning 96 ± 6 steps/min), falls in the range of walking patterns of able-bodied subjects. Looking at the vGRF profiles, the typical physiological pattern, i.e. the double-peak curve, characterizes both limbs.

It is a worth noting that the better gait performance of Subject #3 are related with many factors: on the one hand, transtibial amputation causes less severe impairment of the gait if compared with the transfemoral one, on the other hand Subject #3 had a longer period of use of the prosthesis (indeed, he did not need any walking aids) and was the youngest among the three subjects.

To conclude, this preliminary study demonstrates that wireless pressure-sensitive insoles can be powerful tools in the clinical assessment of gait abnormalities; even though the results turned out to be in line with the data reported in previous works, a larger study with a consistent number of amputees is required to validate the system for a clinical use.

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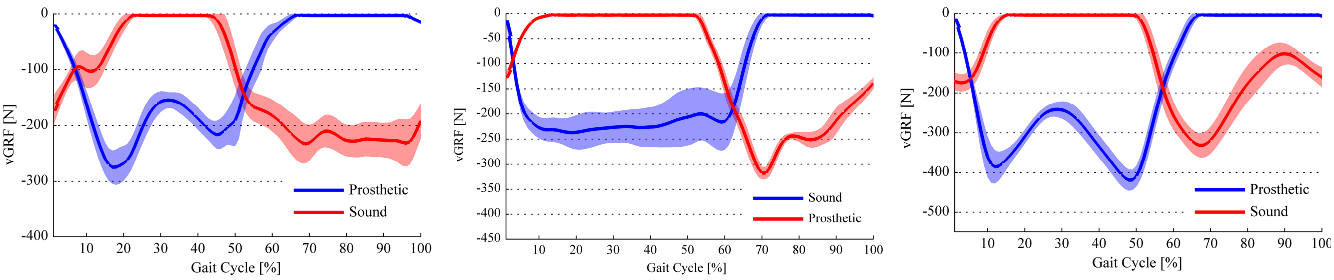
(a) (d)

Fig. 1. (a) Subject #1 wearing instrumented shoes and walking along the corridor. The subject walks with two crutches. (b) Overview of the sensorized insole with electronic board and lithium battery. (c) Electronic board. (d) Intrumented shoe.



(a) (b) (c)

Fig. 2. Average vertical ground reaction force over a gait cycle of the three subjects. Left and right curves are always represented, respectively in blu and red. The legend in each panel specifies which curve represents the prosthetic and sound limb. (a) Subject 1. (b) Subject 2. (c) Subject 3.