Development of an Experimental Set-Up for Providing Lower-Limb Amputees with an Augmenting Feedback*

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Abstract. We present a proprioceptive feedback system for lower-limb amputees based on vibratory stimulation applied on the thigh. The system should be integrated in the prosthesis for overcoming the missing proprioceptive information from the amputated foot sole. It acquires data from one pressure-sensitive insole, inserted in the shoe of the amputated foot, and elaborates the acquired information for the real-time detection of specific gait-phase transitions. On the basis of the recognized transition, one of the vibrators positioned on the amputee's thigh is activated.

1 Introduction

Lower-limb amputees who successfully ambulate with the help of passive or active prosthesis, can often experience many side effects resulting from the absent proprioceptive information from the amputated limb [1]. The lack of information from muscle spindles in muscles from around the knee and ankle, Golgi tendon organs and skin receptors in the foot sole has been demonstrated to yield amputees to walk with adapted gait patterns [1][2]. The asymmetry in walking as well as imbalance postures [3], caused by the impossibility to feel the position of the plantar center of pressure, during every-day activities, may lead to an increased load on the intact limb causing, in the long term, important musculoskeletal problems [4].

In addition to this, the missing proprioceptive information from the amputated foot sole is the reason of the high cognitive effort required to amputees for walking even in highly predictable environments [5]. This aspect is important also when considering the psychological acceptability of the device [6].

The goal of this study is therefore to present an augmenting feedback system to be integrated on lower-limb prosthesis, aimed to convey missing proprioceptive information to the amputee.

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A conceptual description of the feedback system is reported in Figure 1. It is based on one pressure sensitive insole inserted in the shoe of the prosthetic foot, for the extraction of some biomechanical variables of gait (the ground reaction force and the position of the plantar center of pressure), a processing unit for the real-time detection of critical gait events (heel strike, mid stance, toe off) and finally a transduction unit, that closes the loop with the amputee and provides information about transitions between gait phases. The transduction unit consists of small vibrating motors, called vibels, that can evoke to the user a tactile stimulation, being at the same time noninvasive and highly acceptable [6][7].

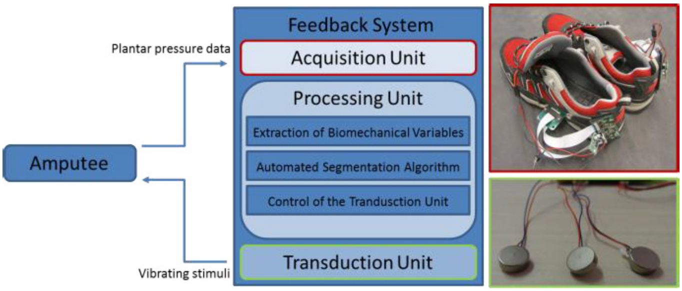

Fig. 1 Concept of the augmenting proprioceptive feedback module. The feedback system acquires data from the pressure-sensitive insole worn by the amputee and elaborates information to provide the amputee with vibrotactile stimuli on the basis of specific gait events. Vibels are shown in the picture below.

2 System Design

2.1 Acquisition Unit

The amputee is required to wear comfortable athletic shoes, the one of the prosthetic leg being equipped with an in-shoe pressure-sensitive insole. This device is made of an array of 64 optoelectronic pressure sensors embedded in a layer of silicone. The sensor technology was presented in [8][9], and applied to measure a wide range of different loads. The sensor array measures the pressure over the plantar area (with the exception of the plantar arch), and transmits the data sampled at 100 Hz, wirelessly to a remote data logging processing unit (maximum data lag is about 40 ms). This sensorized insole can fit into a normal sneaker shoe of EU size 42. Foot sizes from 41 to 43 can fit comfortably in the instrumented shoe as well.

2.2 Data Processing and Gait Segmentation

The 64 voltage signals acquired from the prosthetic foot, are converted into pressure values through a pre-computed calibration function (see [9]). The smoothed pressure map is used to extract the values of the vertical ground reaction force (vGRF), the position of the center of plantar pressures (CoPx, CoPy) and their first-order-time derivatives. All these variables are classically employed to divide the gait into phases [10].

The biomechanical variables are used to on-line segment the gait cycle into 3 phases:

- *Stance 1* (ST1): it starts with the heel-strike of the prosthetic foot and finishes when the body weight is aligned with the artificial forefoot.
- *Stance 2* (ST2): it starts from the end of the ST1 and finishes with the toe-off of the prosthesis.
- *Swing* (SW): this phase includes the whole swing phase of the prosthesis, starting with the toe-off and ending with its next heel-strike.

The observed signals are modeled by a 3-state Hidden Markov Model (HMM), with 6 observable states (emissions). The method is a simplified version of the model presented and validated in [11], where a dataset made of steady-state steps gathered from full able-bodied subjects walking at different self-selected speeds, was manually segmented by an expert who analyzed the vGRF profiles, and marked the transitory events dividing each cycle into the three phases to allow the estimation of the model parameters $\boldsymbol{\lambda}=(\pi,A,B)$(see[12]). Figure 2 shows an example of manual segmentation on the basis of the vGRF profile.

The method uses the straightforward Viterbi algorithm to decode the current gait phase.

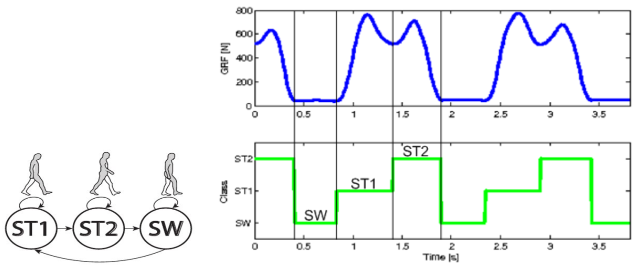

Fig. 2 Segmentation method. On the left the three-state model of gait with arrows highlighting the allowed transitions between phases. On the right, example of segmentation of a gait cycle in sub-phases made by an expert.

2.3 Transduction Unit

Based on the recognition of gait-phase transitions the transduction unit returns to the subject information about the current gait phase. The transduction unit is made of 3 vibrotactile round-shaped motors (Precision and Microdrives, London, UK) with a diameter of 8 mm and a unit weight of 0.8 g. They should be positioned on the thigh of the residual limb at different heights.

Motors are chosen to be easily wearable and confortable, having extremely low encumbrance, and typical vibration amplitude (0.7 g) and frequency (200 Hz), both in the perceivable range experienced by the human hairy skin [13].

A microcontroller-based electronic board drives the vibels. Each miniature motor is controlled through a MOSFET driven by a PWM signal. Vibration frequency and amplitude are proportional to the PWM duty cycle. This technology was previously used to give a feedback on upper-limb prosthesis users in [13][14].

The activation of each vibel is linked with the recognition of a specific gait phase transition, and it is set for a time duration of 0.1-0.2 s in order to be perceived by the user during walking and to avoid overlapping of vibrations of different vibels which can increase the difficulty of the user in recognition of the activated vibel.

3 Discussion and Future Works

While walking with a full-able body is a cognitively undemanding, almost automated task, walking with a prosthesis is a more complex task that places higher demands on cognitive systems. The presented proprioceptive feedback system has been realized to be integrated with active lower-limb prosthesis to make walking the most intuitive and cognitively undemanding possible by sending vibrotactile stimuli to the amputee when specific gait phase transitions are detected. This information gives an idea about the position of the plantar center of pressure on the prosthesis sole, facilitating the user in maintaining a good posture and avoiding adapted gait patterns during walking.

Future works will be focused on the validation of the vibrotactile elements for the assessment of the subjective perception of the transduction unit in terms of the user's ability in the discrimination of which vibel is active. Furthermore the entire setup will be assessed by simple walking exercises with lower-limb amputees.

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