A new sensory feedback system for lower-limb amputees: assessment of discrete vibrotactile stimuli perception during walking

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***Abstract*—Sensory feedback systems can improve gait performance of lower-limb amputees by providing information about the foot-ground interaction force. This study presents a new platform designed to deliver bilateral vibrations on the waist of the user, synchronously with specific gait events. Preliminary perceptual tests were carried out on five healthy subjects to investigate the perception thresholds on the abdominal region. The reaction time and the percentage of correct perceptions were computed to compare three stimulation levels: 50%, 70% and 100% of the maximum vibration amplitude (i.e., 1.5g, 1.9g and 2.2g). The reaction times decreased with higher activation levels. The percentage of correct perceptions was 40% with 50% stimulation level and higher than 97% with 70% and 100% stimulation levels, respectively. The results suggest that vibration amplitudes of 1.9g provide vibrotactile stimulation that can be effectively perceived during walking, thus used to convey sensory information.**

I. INTRODUCTION

LOWER-limb loss is a major disabling condition, typically causing abnormal gait kinematics, higher metabolic consumption, back pain and secondary joint and bone disorders [1]. Altered sensory-motor afferent feedback is a primary determinant of these impairments. Although amputees can rely on the forces acting at the stump-socket interface for maintaining balance in standing or during locomotion, the development of a sensory feedback device that can provide information about the foot-ground interaction is considered a promising solution to improve gait performance and increase the outcomes of rehabilitation [2]. Vibrotactile stimulation, in particular, is among the most preferred solutions to provide feedback due to its minimal invasiveness, high acceptability and cost-effectiveness.

A previous study conducted by our team demonstrated that gait symmetry can be improved by delivering unilateral discrete vibrotactile stimulations synchronously with specific gait events [3], [4]. Despite the promising results, the previous study required a multiple-day training phase to let the amputee learn how to take benefit from the sensory information, i.e. how to associate the haptic feedback to a more physiological gait pattern. In this study, we describe a novel sensory feedback platform for lower-limb amputees, designed to improve the intuitiveness of the discrete event-driven stimulation strategy by delivering bilateral short-lasting and low-intensity vibrations at the occurrence of specific gait phase transitions, in order to provide feedback from both the sound and the prosthetic limbs. Along with the presentation of the system, we report a preliminary study on the vibrotactile perception capability of five healthy subjects under dynamic conditions, with the ultimate goal to identify suitable low-intensity stimulation levels for providing effective feedback during walking.

II. MATERIALS AND METHODS

A. Experimental setup

The sensory feedback device used in the present study consisted of three main hardware modules, as shown in Fig. 1: a pair of pressure-sensitive insoles, a control board (namely, the Vibro Board) and 12 vibrating motors (VT units) attached to a commercial belt adjustable in size.

Each insole comprised an array of optoelectronic sensors [5]. Pressure data were wirelessly transmitted to the real-time processor of the Vibro Board (sbRIO 9651, National Instruments, PHX, USA), where the instantaneous centre of pressure and the vertical ground reaction force were estimated in real-time. According to the calculated biomechanical variables, three gait phases were identified, similarly to [1]. Concurrently with gait phase transitions, the Vibro Board generated the commands to activate one VT unit with a specified intensity.

Each miniaturized VT unit was made of an eccentric

Fig. 1. Experimental setup. a) A subject on the treadmill during the experimental session. b) Distribution of the VT units around the trunk. c) VT units encapsulated in the PDMS matrix and attached to the belt. d) Instrumented shoes housing the pressure-sensitive insoles.

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rotating mass motor (Precision Microdrives, London, U.K.) encapsulated in a matrix of PDMS. The smoother contact area of the silicon layer was conceived to increase the comfort for the user without degrading perception, thanks to the wider contact area. The selected vibrating motors could reach a vibration amplitude of 2.6g when operating at rated-speed. However, due to the inertia of the eccentric mass, and the presence of the silicon layer, the actual vibration amplitude is lower than the maximum value when activated for short times. A preliminary analysis showed a vibration amplitude of 2.2g with a vibration duration of 100 ms. The VT units were attached to the belt and equally spaced at a distance of 5.5 cm from each other (consistently with the tactile spatial resolution on the abdomen [6]).

B. Experimental protocol

Five able-bodied subjects (one female, age 26.6±1.1; weight 65.2±10.6 kg; height 1.74±0.04 m; foot size 41-43 EU) were recruited for the study. They were asked to walk on a treadmill at self-selected speed while wearing the instrumentation. Prior to the experiment, a short session was performed to let the subjects familiarize with the activation of the VT units. During the perception test, each VT unit was activated according to a pseudo-random sequence to deliver 100 ms bursts of vibration at three different levels of intensity, (50, 70 and 100% of the maximum amplitude, corresponding to vibration amplitudes of 1.5g, 1.9g and 2.2g, respectively), and synchronously with one of three gait events (heel-strike, foot-flat, toe-off). Every time they perceived a vibration, the subjects were required to press a button connected to the Vibro Board as quickly as possible and communicate which VT unit they perceived as active.

The stimulation duration of 100 ms was selected to achieve clear perception without overlap between successive vibrations, annoyance or adaptation effects [3], [4], [7], [8]. The number of steps occurring between two consecutive activations was randomized to avoid possible bias due to expectation. Each stimulation was repeated 4 times. In total, 432 activations were tested (12 VT units, 3 phase transitions, 3 intensity levels, 4 repetitions).

C. Data Analysis

A MATLAB routine (MathWorks, Inc.) was developed for offline data elaboration. The percentage of correct perceptions was calculated for each stimulation intensity. The Reaction Time (RT), i.e. the elapsed time between the VT unit activation and subject response, was calculated. Missing recognitions were not considered in the computation of the RTs. Mean RTs and correct perceptions of each stimulation level were extracted for each subject and then the across-subject median values were computed.

III. Results and Discussion

Fig. 2 shows the across-subject median and interquartile range of the RT and overall percentage of correct perceptions, for each stimulation level. Overall, the RT resulted lower with higher stimulation levels (700 ms, 602 ms and 562 ms, respectively with 50%, 70% and 100% stimulation levels). The percentage of correct perceptions was 40% with the lowest stimulation level and higher than 97% with 70% and 100% stimulation levels. A similar trend was observed in a previous study [8], where the RTs were computed to compare three vibration frequencies: 140, 180, and 220 Hz, with the latter resulting in the shortest RT.

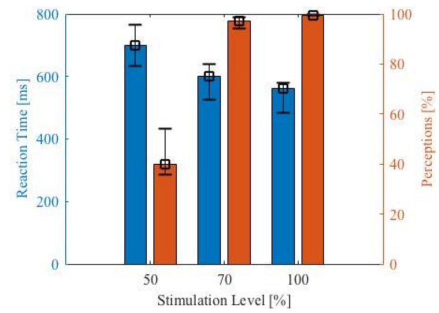

Fig. 2. Median ± interquartile range of reaction time (in blue) and percentage of correct perceptions (in red) for each stimulation level.

The main purpose of this work was to analyze the subjects' perception thresholds on the abdomen, when vibrating stimuli are delivered during walking. So far, psychophysical studies have identified the minimum skin displacement and stimulation frequency required for detecting vibration on the abdominal region in static conditions (4-14 µm at 200 Hz) [7]. However, it is unknown whether the ambulation condition can affect perception.

Our results suggest that perception thresholds on the abdomen during locomotion fall between 50% and 70%. As expected, the maximum level (100%) showed the best performance. Nevertheless, at 70% vibrations were already clearly perceived by the subjects. Therefore, in order to achieve a trade-off between comfort and correct perception, the stimulation level shall be set at 70%, as high intensity vibrations might induce skin adaptation effects or be perceived as bothersome by subjects, in long-term utilization.

Future studies will investigate the capability of the device to improve the gait performance of lower-limb amputees.

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