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A Wireless Sensory Feedback System for Real-Time Gait Modification

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***Abstract*— Current rehabilitation technology and techniques have proven effective at modifying and correcting gait abnormalities. They are however limited to laboratory and clinical settings, under the supervision of a specialist. Conventional techniques for quantifying gait asymmetries can be combined with sensory feedback methods to provide an intuitive and inexpensive feedback system for extra-clinical rehabilitation. A wireless feedback system has been designed to collect gait information, process it in real-time, and provide corrective feedback to the user. The corrective feedback can be presented through visual, audible, or vibrotactile methods, or a combination thereof. Initial results have led to improvement in the sensory interface of the device to maximize the corrective influence on inexperienced subjects. These preliminary findings suggest that the wireless feedback device can influence the gait of the user, and effectively adapt to their personal feedback preferences.**

I. INTRODUCTION

In normal human behavior, walking is an integral motor function for means of locomotion and transportation. Normal gait is an important attribute of walking and can often be compromised by a range of different abnormalities and impairments. Due to the impact that gait abnormalities can have on the quality of life, many different methods of diagnosis, classification, and treatment have been developed [1]. One form of rehabilitative treatment, used in many different muscular and articulation disorders, is the use of sensory feedback to present corrective information to the patient [2-4]. While some investigation has been done into using sensory feedback to correct aberrant gait [4-6], the equipment used is often large and stationary, requiring the patient to attend therapy sessions in a gait or physical therapy lab [6,7].

Due to the personnel and equipment demands inherent to traditional gait rehabilitation, a portable feedback system would greatly increase the availability of treatment options for patients suffering from an abnormality. An effective rehabilitative method that could be used with minimal instruction from the therapist would accelerate the patients return to normal gait, while requiring less in the way of resources and clinical supervision. This paper presents work done to continue the development of an inexpensive insole sensor system to collect gait data, and the methods used to convert and present the data as sensory feedback to the user.

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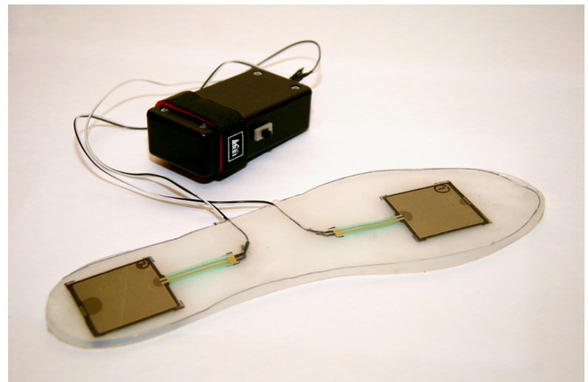

Fig. 1. Instrumented insole system and wireless data collection box

A. Previous Work

Sensor insole systems have previously been developed to collect ground force reaction and gait asymmetry data using force sensitive resistors (FSRs) mounted in silicon shoe insoles [8,9]. This insole system has been tested and verified to provide reliable gait data, for use in quantifying the gait ratio and gait index of a patient characterized as having an asymmetry [10]. Initial tests using sensory feedback have shown that audible feedback is an effective method of improving the gait of subjects who have undergone lower limb amputations and are walking on prosthetics in terms of decreasing trunk sway and improving stance time symmetry [11].

B. Motivation

The insole sensor systems have been shown to provide accurate and effective gait feedback, and are an improvement in terms of portability and adaptability to traditional gait sensors systems such as a force plate or motion capture camera. They are not however, entirely portable and still require the use of a laptop computer for data analysis and feedback. This paper presents the development, fabrication, and testing of a portable, unobtrusive feedback device for use with the insole sensor system, as shown in Figure 1.

II. METHODS AND DEVELOPMENT

A custom sensory feedback system has been designed and fabricated for use in gait rehabilitation. Initial tests have been performed to tune the feedback methods in anticipation of a device verification study. It is anticipated that 15 subjects will participate in the study, wherein the ability of the feedback system to introduce gait abnormalities in otherwise healthy participants will be quantified.

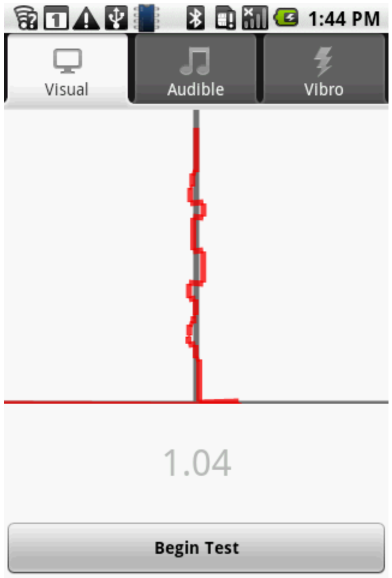

Fig. 2. Initial visual feedback display

A. System Design

The instrumented insole system has been designed to collect stance information from each individual foot, and transmit it to the feedback device for presentation to the user. As shown in Figure 1, each instrumented insole has two pressure sensors, oriented to record the initial (heel strike) and final (toe off) contact for each limb during subject ambulation. The silicon insole is designed for adaptability and implementation with different shoe sizes. The sensor setup is initialized simply by placing the instrumented insole inside the individual's shoes and in turn securing them to the foot.

The stance data is collected using an Arduino microcontroller contained in a small box attached to the subjects ankle. The data is then processed and transmitted to the feedback unit via Bluetooth wireless communication. The foot sensor system is completely contained within the insole and ankle box, providing an unobtrusive, durable, and adaptable system for use in a wide variety of rehabilitation environments.

In selecting an interactive device for use with the lower limb feedback system, a set of criteria were established. It was specified that the device must adequately provide three different methods of sensory feedback (visual, audible, and vibrotactile), and be lightweight and portable, so as not to burden the subject unnecessarily. A smartphone was selected for use due to the integrated sensory feedback systems, and relatively ubiquitous availability in modern society. In addition to fulfilling the required feedback criteria, the use of a smartphone also established the ability to develop an interactive feedback program that could run on existing hardware, rather than requiring the use of a dedicated feedback device.

The Android platform was chosen for development of a feedback application due to the unrestricted development and distribution structure of the Open Handset Alliance. The primary feedback application was designed to control and present the user with three different feedback methods: visual, audible, and vibrotactile (see Figure 2) Upon startup of the application, the user is able to select from one of the three different sensory cues, or a combination of two or more. The stance time recorded by the insole sensors and subsequently transmitted to the smartphone is then used to determine the gait asymmetry ranking[10] and present it to the user according to their selected feedback preferences.

B. Feedback Design

For all three forms of feedback, a set of asymmetry thresholds was established, with the user able to select between strict and flexible feedback parameters. If the gait rating of the user falls outside of the specified limits, then the selected method of feedback will notify them of their asymmetry and allow them to correct it. For the audible feedback, this constitutes a single beep if they are spending too much time on their left limb, and a double beep if they are spending too much time on their right limb. Similarly, if they have initialized vibrotactile feedback, they will receive a short or long vibrating pulse corresponding to respective left and right gait asymmetries.

The method by which the visual feedback is presented is through a rapidly updated graph with the gait symmetry ratio normalized to fall nominally at 1 (see Figure 2). Deviations from the optimal gait ratio are easily recognizable to the user through visually observing the gait line to move to the left or the right. Visually observing the feedback line to fall to the right of the optimal ratio signifies that the user is spending too much time on their right foot, with the converse true for the left foot.

III. Initial Device Results

The initial testing of the device used three subjects who were asked to use the gait feedback system and provide feedback regarding the user interface. The subjects were between the ages of 21 and 25, with no history or clinical

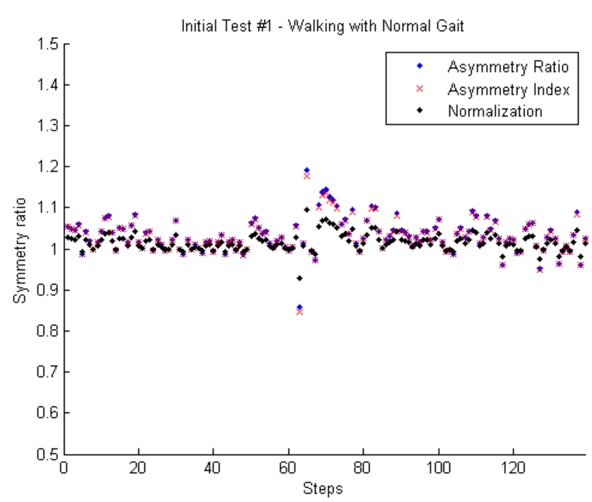

Fig. 3. Subject 1 walking test results

diagnosis of gait abnormalities. They were asked to walk normally while the feedback system recorded their stance time and displayed their gait symmetry ratio. The plot of one such walk is shown in Figure 3, along with several different methods of calculating the gait asymmetry such as the asymmetry ratio, asymmetry index, and normalization [10]. These methods for calculating the gait asymmetry have been previously tested and evaluated for use in a number of different applications [10], including work done on the previous iteration of this insole system [8]. From the previous work and these initial testing results, it was decided to quantify the gait by calculating the asymmetry ratio, as shown in equation 1.

$$asymmetry\_ratio = \frac{left\_stance\_time}{right\_stance\_time} \tag{1}$$

From Figure 3, it can be seen that the different methods provided very similar asymmetry values despite differing complexity in each method's calculations. With regards to the efficacy of the device at providing feedback on their walk, there was a consensus among the test subjects that the graph updates were too sensitive and came too quickly for them to positively identify and respond. In addition, the subjects felt that the asymmetry thresholds at which vibrotactile or audible cues were given were arbitrarily difficult to remember and follow, with no definitive display for them to draw reference from.

The comments received regarding the feedback methods during the initial testing have resulted in changes to the visual display to make it more intuitive to the user. The visual display was updated to have a clearly delineated area bordered by the left and right gait asymmetry thresholds. The graph update was also changed to draw a single vertical line corresponding to each update of the asymmetry ratio, rather than an individual data point as was previously performed.

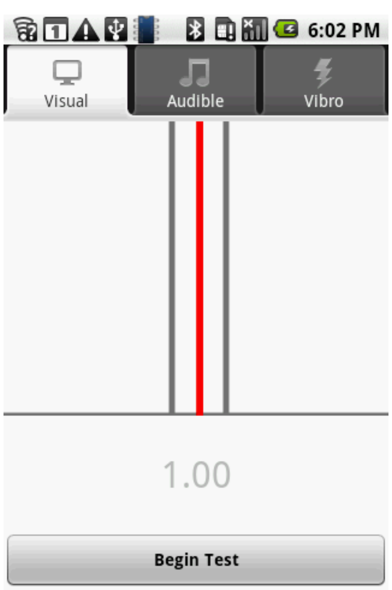

Fig. 4. Revised visual feedback display

The revised user interface (Figure 4) also updates less frequently, allowing the gait data to be fully addressed by the user without overloading them with information.

IV. Discussion and Future Works

The purpose of designing an instrumented insole system that is capable of giving real-time feedback to the user is to reduce the need for bulky equipment and personnel resources in gait rehabilitation and therapy. In this respect, the device has been designed to take advantage of feedback systems that are already available to the prospective users, and provide them with a sensory interface that is both intuitive and effective. Previous versions of the device [8] have indicated the usefulness of audible feedback in gait training, as well as the need to provide and implement a truly mobile form factor for use in settings outside of the traditional clinic. This new device builds upon the previous version by including both visual and vibrotactile [4] feedback methods, in a portable and easily implementable system. The use of a smartphone to implement the sensory feedback is also new to this device, and has been refined through both observational and analytical methods in preparation for subject testing.

In order to ensure that the feedback device and user interface met the specified criteria, some initial testing was performed prior to beginning the device efficacy study. Through the suggestions received, changes were made to the different modes of feedback that improved the overall usability of the device. Through this detailed design and refinement process, the device has been improved and is currently being used in a participant study to quantify its ability to influence the user's gait. It is anticipated that there will also be a future study to examine and compare the results of the wireless gait asymmetry system against current offerings.

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