A Wireless Sensory Feedback Device for Real-Time Gait Feedback and Training

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***Abstract*—This paper presents a new sensing and feedback system for a personal gait rehabilitation device based on wireless transmission of ambulation data for real-time sensory feedback for assistive healthcare. An integrated force-sensing insole was designed, using embedded force sensitive resistors that were sampled using a microprocessor, which then transmitted the data to an Android smartphone for presentation to the user. Experiments were performed to verify that the device captured accurate gait data, and was able to influence the gait of the subject. In addition, different sensory methods of feedback were tested to determine their individual efficacy at modulating the gait of study subject. The results show that the feedback system is capable of influencing the gait of the user, without the need for direct supervision by a rehabilitation specialist. In addition, a statistical analysis was performed to establish the reliability and repeatability of the system. From these results, this feedback system is established as a novel, inexpensive, and effective candidate for use in clinical rehabilitation of persons with gait abnormalities.**

***Index Terms*—Gait rehabilitation, sensory feedback, wearable sensors.**

I. INTRODUCTION AND MOTIVATION

THE ability to walk is an essential motor function for normal human locomotion and transportation. Healthy ambulation is required of nearly all persons on a daily basis, and can be necessary for employment, recreation, and general movement. Due to the functional importance of walking, consideration must be given to the treatment and remediation of disorders affecting the ability to walk properly and without difficulty [1]. There are many different methods for evaluating and diagnosing gait problems, with different classifications for severity of the disorder based on the level of functionality as compared to a healthy gait [2]. Proceeding from the initial diagnosis, specialized rehabilitative techniques have been established and are used by clinical therapists to correct the abnormality [2], [3]. The objective of rehabilitation is to raise the functional walking ability of the patient to a level, where they are able to perform normal tasks and are not at risk for subsequent health defects. Due to the high variability in the causes and manifestation of gait disorders, rehabilitative methods are often highly specialized to the individual patient [1]. Because of this specialized attention, there is a high resource demand, which is common to most forms of rehabilitative therapy. This resource demand includes the time spent with the therapist, expensive instrumentation and training devices, and the use of a gait lab and its associated overhead [1], [4].

Current systems used in gait rehabilitation and training include force plates, force mats, motion capture systems, instrumented treadmills, and insole sensor systems [5]. Force plates and force mats are ideal for use in stationary settings due to their high accuracy, but require training for use and are prohibitively expensive and large to be considered for implementation outside the clinic [5]–[7]. Instrumented treadmills are able to gather large amounts of step data, but are limited by their controlled environment and prescribed walking pattern [8]. In addition to stationary gait analysis systems, patient mounted systems are available to measure gait parameters [9]. While different implementations of these mobile systems have been evaluated and shown to provide accurate gait data [5], they are often prohibitively expensive (over US$10,000), and require complicated peripheral equipment and specialized training for use [10]–[15].

Given these constraints, other researchers have developed alternatives for rehabilitation. One example is a novel air bladder sensor for gait analysis [16]. This system was subsequently used for mobile feedback using a custom device for analysis and feedback [17]. Another approach provided visual–auditory feedback to amputees based on force sensors, but required a desktop computer and monitor for the feedback; the device was used in conjunction with a treadmill and was received well by the amputee subjects [18]. Other biofeedback systems have been developed for balance in older adults. While one requires a computer monitor for operation [19], other researchers have provided the feedback directly using onboard processing and an array of vibortactors [20]. Recently, a force sensor insole and motion sensors were combined with a master node to record running data during a six day competition, and demonstrate that such sensors can be worn over long periods of time and result in meaningful data for analysis of gait and movement [21]. In response to these specialized gait rehabilitation devices and their associated drawbacks, a novel insole sensor system has been developed to provide an inexpensive and accurate method for gait feedback and training [5], [22]. This sensor system, previously titled the lower extremity ambulatory feedback system (LEAFS), was designed and validated against current clinical systems for use in gait training of subjects with unilateral transtibial amputations [5]. LEAFS used a netbook to provide a single type of feedback, consisting of a simple auditory alert.

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The purpose of this paper is to build upon this previous work in the design, manufacture, and verification of an inexpensive and portable gait feedback device for use by patients outside of the traditional clinical environment. A major goal of this paper is to develop a system that can ultimately be available at low cost for use in rehabilitation. The system is capable of determining common gait parameters through force sensitive resistors (FSRs) embedded in a custom insole that can be easily implemented in a patient's existing shoes. An ankle-mounted microcontroller provides sensor sampling and data collection capabilities, as well as the ability to transmit real-time gait data wirelessly via a Bluetooth serial connection. The netbook used in the LEAFS system was replaced by a smartphone, and an extensive application (app) was developed for the Android mobile phone operating system. This enables an Android phone to receive the gait data and use the phone's functionality to provide effective and intuitive sensory feedback to the user. The app provided three types of feedback, the same auditory alert as in LEAFS, plus a similar vibrotactile alert, and a visual display. By accurately measuring gait data and providing rich feedback to the user, the system provides an inexpensive and valuable tool for potential use in clinical and extra-clinical rehabilitation.

While implementing feedback on a smartphone places some limitations on the design (since the smartphone hardware is designed for another purpose), avoiding a custom feedback device or use of a personal computer reduces the ultimate cost of the system considerably. With nearly 1 billion smartphones projected to be in use worldwide by 2015 [36], accompanied by increasing use of tablets and similar devices, it is not unreasonable to assume that subjects will have access to a basic smartphone. The overall low cost, ease of installation, and intuitive nature of the device provide for an effective method of gait modification, without the direct supervision of a clinician or rehabilitative specialist.

II. DEVICE DESIGN

The design priorities to develop this assistive personal care device and with respect to improvements being made on the previous system were: simplifying the wireless communications protocol, improving the modularity and robustness of the system, and developing a highly customizable smartphone application that is capable of providing multiple modes of feedback in an intuitive and easy to use package. To accomplish these functionality goals, the design was separated into physical sections, which were then individually addressed to ensure that the completed subsystems integrated successfully into a reliable and inexpensive gait feedback device. The individual system design components are discussed here and titled the adaptive, real-time instrumentation system for tread imbalance correction, or ARTISTIC.

A. Embedded Insole Sensors

The insole sensor system made use of force sensitive resistors (FSR, INTERLINK Electronics [23]) to sample plantar pressure data. The insole was molded from polydimethylsiloxane, with two square FSRs embedded per foot; one sensor under the forefoot, and one sensor under the hindfoot, as shown in Fig. 1. This design departs from previous iterations in which a layout of up to ten FSRs per insole was used. This change in design greatly decreases the amount of data that are collected and analyzed, thereby simplifying the entire system and increasing the sampling rate. Two sensors per insole are sufficient to calculate gait timing and provide feedback on abnormalities [33], and the parameters used to determine the user's level of gait abnormality can still be effectively calculated, without extra and unnecessary data being sampled. The drawback to this simplification is that the ARTISTIC system is unable to evaluate the center of plantar pressure, which is capability that the previous LEAFS system had. The remaining components in the system are modular in their design however, and the ARTISTIC system could be easily modified to accept a greater number of insole sensors in a future iteration. The FSRs are mounted in an orientation in which they will be immediately depressed upon heel strike, and released upon toe off. The FSRs are arranged in a voltage divider circuit that converts the resistance change caused by sensor activation into a change in electrical voltage. This corresponding voltage change is then sampled using the microcontroller's analog to digital chip for data analysis. The insole sensors are divided into two different sections, a forefoot section, and a hindfoot section. By nature of this orientation, different shoe sizes can be accommodated through arrangement of the insole sections within the shoe.

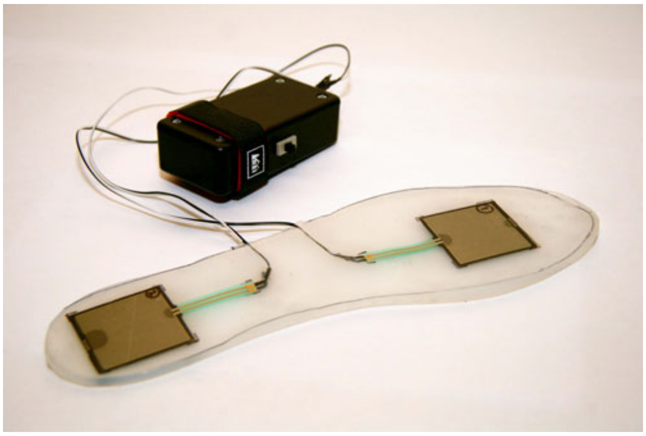


Fig. 1. ARTISTIC insole system; microcontroller, Bluetooth chip, conditioning circuitry, and 9-V battery are contained within the ankle-mounted box.

B. Microcontroller and Wireless Data Transmission

The data are sampled from the insole sensors by an Arduino Pro Mini microcontroller, using the ATMEGA168 16-MHz microprocessor. The FSR data are transmitted to the Arduino using two of the possible six analog input pins, any of which can be read simultaneously. The Arduino board is in turn connected to a BlueSMIRF Gold Bluetooth serial pipe for data transmission to the Android smartphone. The BlueSMIRF Gold chip is capable of wireless serial data transmission and receipt when paired with the feedback application running on the smartphone. While possible implementation of a ZigBee radio for communication with the smartphone was investigated for its low power consumption, Bluetooth serial communication was eventually chosen due to the ubiquitous support for Bluetooth protocol in modern smartphones. As ZigBee wireless communication becomes more fully supported across android hardware, it will provide a viable long-term solution to the more power-hungry Bluetooth protocol. Power to the microcontroller and associated circuits is provided by a standard Alkaline 9-V battery, connected through a PQ3RD13 voltage regulator. All of the components associated with the microcontroller circuit are housed in a $1.5'' \times 4''$ plastic project box, which is strapped to the ankle during use (see Fig. 1). This system, in addition to the embedded insole sensors comprises the entire lower limb implementation of the ARTISTIC system, and fulfills a primary goal of inexpensive implementation with an associated prototype cost of $225 USD.

C. Smartphone and Feedback Development

As noted previously, current systems that analyze gait and provide feedback to the user are stationary and often cost prohibitive [5]. In addition, they require the careful supervision of a rehabilitative therapist or specialized operational training. While the benefits of traditional gait rehabilitation and therapy are numerous and effective [4], there exists a lack of smart feedback systems for use in home or other nonclinical settings. A major motivation in the continuing development of this research is the ability to provide a nonintrusive wearable instrumentation system to augment and support traditional rehabilitation. In order to achieve this goal while still maintaining low-cost and accessibility, previous iterations of this insole system have relied on laptop computers running MATLAB or LabView to analyze and present gait data [5]. While the use of portable computers for data collection and presentation is a significant improvement upon stationary feedback installations, it still requires the use and possible transport of an unwieldy and heavy device for any time in which the user wants to employ the feedback system. Thus, one of the major design specifications established for the development of the ARTISTIC system was the integration and development of a highly portable feedback device.

In the preliminary design phase, a literature search was performed to determine the different types of sensory feedback to be included in the next generation ARTISTIC feedback device. Different applications of sensory feedback had effectively made use of visual [24], audible [25], and vibrotactile [26], [27] methods to effect a motor response in test subjects. These three methods were chosen for investigation and used as feedback cues with the redesigned insole gait system. In addition to the feedback methods, another design specification concerned the form factor of the portable feedback device. The established requirements for the redesigned device were to provide different modes of feedback from a fully integrated system, communicate wirelessly with the insole sensor, and be supported and carried with only one hand. Because a custom feedback device would increase both cost and complexity, a smartphone was selected for the ARTISTIC system.

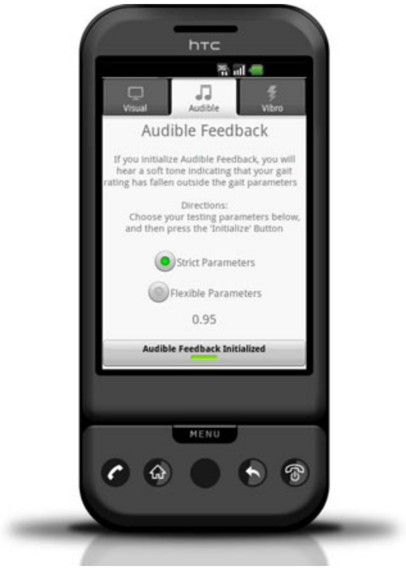
At face value, smartphones offer a wide variety of useful and effective methods for conveying data to the user. They also include other desirable aspects for use in research applications including fast processors, large storage capacities, and several methods of wireless communication [28], and are relatively ubiquitous in much of modern culture. By developing a feedback protocol to work with the patient's existing phone, the need to carry an extra device is therefore mitigated, without sacrificing functionality or form. For the ARTISTIC system, it was decided that an Android smartphone would be used for developmental purposes, and during efficacy trials. The reason for choosing the Android platform over other competing platforms is due to its development and control by the open handset alliance, allowing for greater accessibility and developmental freedom. The entire operating system and platform are open source and free, which allows for flexibility in development and greater creative license [29]. The benefit of developing a feedback protocol for use on the Android system is directly related to the ease in which the peripheral phone systems can be accessed and implemented within an application, or app. These peripheral systems include speakers, vibrating motors, touch sensitive display screens, input keyboards, and internal GPS, and accelerometer units. In addition, wireless communication is available through the use of the Wi-FI service (IEEE 802.11) or Bluetooth communication. A custom ARTISTIC application was designed and written for implementation on the Android system. This app uses the peripheral phone systems to provide visual, audible, or vibrotactile feedback cues to the user, and influence their gait accordingly.

Fig. 2. ARTISTIC Android; application layout, figure adapted from [32].

III. ARTISTIC ANDROID APPLICATION

The design and interface of the ARTISTIC application is meant to allow the user to monitor and receive feedback regarding their gait at any time during normal walking. In order to accomplish this assistive healthcare feedback, an efficient and intuitive application layout was developed to allow the user to quickly connect to the insole sensors, and specify which singular

Fig. 3. ARTISTIC visual feedback tab.



Audible Feedback

If you initialize Audible Feedback, you will hear a soft tone indicating that your gait rating has fallen outside the gait parameters

Directions:
Choose your testing parameters below, and then press the 'Initialize' Button

● Strict Parameters
○ Flexible Parameters

0.95

Fig. 4. ARTISTIC audible feedback tab.

method or combination of feedback that they desire. The final application layout makes use of a tabbed design in which each feedback method is quickly available via clicking on the corresponding tab, as in Fig. 2. Due to the integrated nature of the app, clicking on a new tab does not end the previous method of sensory feedback, but rather allows the user to add new modes in combination.

A. Data Logging

In addition to the feedback tabs available in the layout, the ARTISTIC application includes context menus for the user to specify their individual details and feedback preferences. This is a valuable component for researchers, as it allows them to easily use the application to log study data regarding the influence of the sensory feedback on the user. Once the user has entered all of their information into the application, it can restore their saved preferences, or be set to record data from their feedback session. At the conclusion of the walk, all of the information can be easily retrieved from the external secure digital (SD) card or via a USB or wireless connection for further data analysis.

B. Visual Feedback

The visual feedback tab is designed to present the user with an intuitive and simple interface containing their current gait details, and whether or not they fall within acceptable parameters (see Fig. 3). The two gray lines denote the acceptable gait range, while a third line displays the user's current gait rating. When the user's gait falls within the given parameters, the feedback line is displayed in green, when it falls without, the line changes to red. The parameters can be changed depending on the user's preferences, which will correspondingly adjust the range of the parameter bars in the visual feedback tab. In addition to the graphical representation of the user's gait rating, a numerical display is shown at the bottom of the screen, as in Fig. 3. The numerical display updates with the current gait ratio each time the patient takes a step, so as to not overwhelm the user with a constant stream of information. The graphical display is deliberately designed to be simple and intuitive, so as to allow the user to quickly glance at the display to receive their current gait status.

C. Audible Feedback

The audible feedback tab provides the user with simple instructions for the initialization and protocols required to successfully start and follow the application's audible feedback. As shown in Fig. 4, the user can specify whether they want strict or flexible feedback parameters, which adjusts the amount of gait deviation before the audible feedback system is engaged to alert the user. When the audible feedback is initialized, the phone plays unique tones corresponding to the user's gait being outside the acceptable range. These tones are nominally output through the phones speaker, but can be sent through headphones if the user prefers. The user can initialize audible feedback and then navigate away from the audible tab and still receive audible cues regarding their gait.

D. Vibrotactile Feedback

Similar to the audible feedback tab, the vibrotactile tab presents instructions regarding the initialization and subsequent receipt of vibrotactile cues corresponding to the user's gait. The tab layout is generally identical to that shown in Fig. 4, with the differing instructions and initialization parameters. When the vibrotactile feedback has been initialized, the phone will vibrate to let the user know that their gait has fallen outside the specified parameters. If the user's gait ratio is too high, corresponding to spending too much time on their left foot, the vibrator will give a long buzz. Conversely, if the user's gait ratio is too low, they will receive a short buzz. The vibrotactile feedback allows the user of the ARTISTIC system to receive silent, low-level feedback cues when the other methods of sensory stimulation are unable to be used, or ineffective due to the user's current environment.

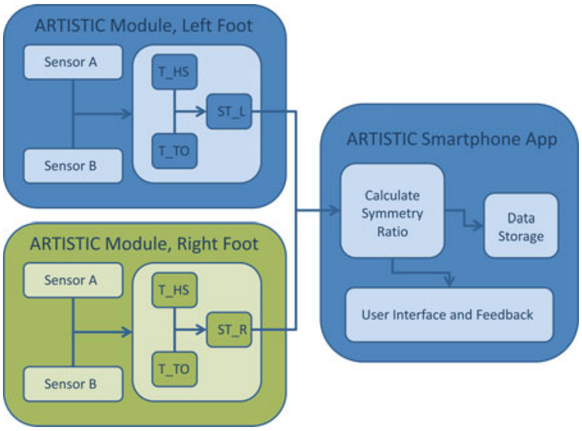


Fig. 5. Data flow in the ARTISTIC system.

IV. TECHNICAL IMPLEMENTATION

The design of the ARTISTIC feedback system has been developed to provide the user a measurement of their asymmetry, a standard clinical quantification of normal or abnormal gait. A diagram demonstrating the process flow is included in Fig. 5.

First, the timing parameters are determined by the microcontroller in the ankle box. This is done using a simple threshold as in (1). The microcontroller samples the sensor data at 1000 Hz. For this implementation of ARTISTIC, the stance time was used for feedback. Stance time is defined as

$$\mathrm{ST} = \frac{\mathrm{T\_HS}}{\mathrm{T\_TO}} \tag{1}$$

where T_HS and T_TO are the times of heel strike and toe off, respectively. Once a new pair of heel strike and toe off times have been received, the stance time for that foot is updated. The most current measurement of stance time is transmitted continuously to the smartphone.

Next, the comparison of the gait timing parameters on the left and right sides is implemented in the smartphone app. Asymmetry ratios are used to assign a measurement to the differential in stride and swing phases of the right and left legs, for diagnosis and measurement of abnormalities in a subject [30]. Different methods for calculating the asymmetry in a subject have been used [31]. These methods were evaluated in an initial user study, and the symmetry ratio was selected for implementation using stance time [34]:

$$R = \frac{\mathrm{ST\_R}}{\mathrm{ST\_L}} \tag{2}$$

where ST_R and ST_L are the stance times measured on the right and left feet, respectively. This ratio is calculated in the smartphone app, after each packet of stance time is received from the respective insoles. This ratio is then displayed to the user. In this way, a longer stance time in the right foot will result in a higher gait asymmetry ratio, and trigger sensory feedback as necessary. For a longer stance time in the left foot, the converse is true. Due to the expected variance of the users gait about a target ratio, an acceptable offset band was programmed into the algorithm, with the parameters being strict or flexible depending on the preference of the user. For all subject testing performed in the validation of the device, strict parameters of target ratio ±0.1 were specified and used.

Fig. 6. Subject with ARTISTIC sensor system.

V. DATA COLLECTION AND ANALYSIS

Following the completion of the ARTISTIC insole system and Android application, validation tests were carried out to verify the ability of the system to receive stance data from the insole sensors, and accurately present the resulting gait ratio to the user. These initial tests and the test subject's suggestions were then used to modify and further develop the individual sensory feedback methods. Next, the ARTISTIC system was used in a participant study to determine its efficacy at modifying the gait of the user [34]. The objective of the study was to determine whether the system could effectively induce a negative gait abnormality in a healthy participant population, meaning they have never been diagnosed with a gait problem. In addition to testing the efficacy of the system, the reliability and repeatability of the system were also tested under conditions that it could reasonably expect to experience during normal operation.

A. *Experimental Procedures*

The human subject testing protocol used in the validation of the ARTISTIC system was approved by the University of Utah Institutional Review Board, under the study no. IRB00047784. Twelve subjects were asked to participate in several walking tests to assess the systems ability to influence gait, as well as the corresponding effectiveness of each of the three different types of sensory feedback. Each subject was first introduced to the system, and given instructions on how to interpret the feedback cues. The subjects were given the choice of using their own shoes for the walking tests, or using sets provided by the research staff. They then installed the insole system inside their shoes, placed the shoes on their feet, and affixed the microprocessor box to their ankles via Velcro straps (see Fig. 6). Once the initial setup was finished, the subject was asked to walk normally down a 200-foot hallway, make a turn at the end, and return to the starting point. During this initial walk, the ARTISTIC system was initialized to receive and store gait data to provide a control against which subsequent walks would be compared. Once the subjects had become familiar with the system and provided a control set of data, they were asked to perform a series of three walks over the study course. During each walk, they were randomly assigned a sensory feedback method as well as an offset gait ratio target. They were instructed to follow the feedback cues, and informed that if the cues were followed correctly, that they would be walking with an induced gait asymmetry, or "limp." Following the initial three tests, in which the subject experienced the use of each type of feedback, they were then surveyed to determine which feedback method they preferred. Next, they were asked to perform three additional walks using their feedback method of choice. The additional walks used target parameters with large offsets to determine the ability of the system to induce a large asymmetry in the gait of the subject. The order in which the walks were performed was determined using a balanced latin square, thereby incorporating counterbalanced measures into the study design to minimize the effects of carryover and subject learning. Following the completion of the walking trials, the subject was asked to fill out a usability survey concerning their experience with the ARTISTIC system. They were asked questions regarding their comfort level with the insoles, their opinion of the efficacy of different methods of feedback, and suggestions that they had for the continued modification and revision of the device.

B. Analysis

The raw data files collected from the twelve different subject testing sessions were first retrieved from the smartphone SD card, and then input into MATLAB for statistical analysis of the results. The statistical analysis was broken down into two different sections.

1) Initial Tests: The raw data from the initial three walking tests were separated into visual, audible, and vibrotactile datasets. These datasets were then organized by the gait ratio asymmetry target that the study participant had been given through the ARTISTIC sensory feedback system. The mean values of these target sets were calculated, and compared against the corresponding set of control walks, using a student's one-tailed t-test. Using this t-test, the null hypothesis that the feedback given to the user has no effect on their gait could either be proved or disproved. If the null hypothesis was disproved, a statistical significance and confidence interval was then assigned to the statistical correlation. Evaluating each of the feedback methods in this way, the ability of the ARTISTIC system was determined, derived from the efficacy of its feedback subsets. Following the statistical tests, a posthoc power analysis was performed using the results of the t-test, to ensure that the number of subjects was sufficient to ensure that a false positive was not obtained. Only statistical results with a power greater than 0.8 were reported in this paper.

2) Preferred Tests: In addition to the randomly assigned feedback tests, the subject was asked to provide their preferred method of feedback, and then participate in three further walking tests using that method. These preferred method datasets were populated using large gait ratio offsets of 0.5 or 1.5 to determine if the feedback device was capable of inducing an immediate and large gait asymmetry with a minimal amount of previous system learning. These datasets were similarly compared against the control group using one-tailed t-test to determine whether the feedback had influence on the gait of the subject. In addition, the mean gait ratio of these preferred subject tests was compared against the desired target offset to determine if the feedback was successful in attaining the specified large gait asymmetry. Due to the very small sample sizes of the audible and vibrotactile preferred feedback tests, those statistical tests are not reported.

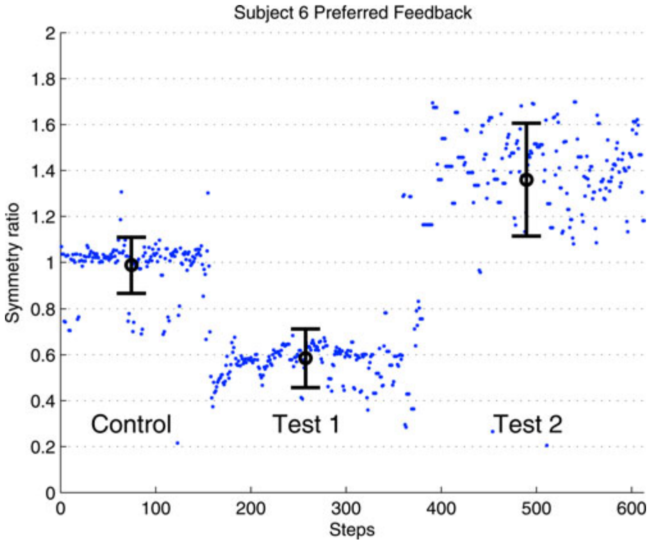


Fig. 7. Subject 6 preferred feedback trials.

TABLE I
STATISTICAL SIGNIFICANCE OF FEEDBACK METHODS

Feedback	Target	P-Value	# of Subjects	Power
Initial Testing				
Visual	1.25	0.0019*	6	0.98
Visual	0.75	0.0443*	6	0.99
Audible	1.25	0.0675	6	0.79
Audible	0.75	0.0853	6	0.97
Vibrotactile	1.25	0.0189*	6	0.45
Vibrotactile	0.75	0.0475*	6	0.97
Preferred Testing				
Visual	1.5	0.0002*	7	0.99
Visual	0.5	0.0119*	7	0.99

*p less than 0.05.

VI. RESULTS

From the statistical analysis of the initial subject tests, it was determined that the visual feedback was successful in modulating the normal gait of all of the test subjects. The calculated average stance ratios and standard deviations are given in Tables I and II. The results of the analysis used to determine if the induced gait asymmetries differed from the control in a statistically significant way are included in Table III. From the p-values calculated, the visual and vibrotactile sensory feedback systems were verified to have induced a statistically significant variance in the subjects gait, while the tests for the audible

TABLE II
SUBJECT TESTING WITH AND WITHOUT THE INFLUENCE OF SENSORY FEEDBACK

ID #	Control	Visual Feedback		Audible Feedback		Vibrotactile Feedback	
	Ratio mean ± SD	Target	Ratio mean ± SD	Target	Ratio mean ± SD	Target	Ratio mean ± SD
1	1.06 ± 0.03	0.75	0.81 ± 0.10	1.25	1.01 ± 0.08	1.25	0.95 ± 0.23
2	1.01 ± 0.11	1.25	1.13 ± 0.09	0.75	0.93 ± 0.12	0.75	0.90 ± 0.10
3	1.13 ± 0.05	0.75	0.89 ± 0.10	1.25	1.08 ± 0.12	0.75	1.05 ± 0.14
4	1.03 ± 0.04	1.25	1.20 ± 0.07	1.25	1.18 ± 0.10	0.75	0.89 ± 0.12
5	1.18 ± 0.04	0.75	0.78 ± 0.05	1.25	1.24 ± 0.04	0.75	0.91 ± 0.09
6	1.01 ± 0.10	1.25	1.55 ± 0.23	0.75	0.64 ± 0.07	0.75	0.63 ± 0.21
7	1.04 ± 0.02	1.25	1.17 ± 0.06	0.75	1.17 ± 0.08	1.25	1.41 ± 0.23
8	1.12 ± 0.08	0.75	0.82 ± 0.11	0.75	0.85 ± 0.12	1.25	0.93 ± 0.25
9	1.08 ± 0.13	0.75	0.99 ± 0.07	1.25	0.98 ± 0.09	0.75	0.99 ± 0.11
10	1.01 ± 0.06	1.25	1.11 ± 0.11	0.75	0.99 ± 0.13	1.25	1.21 ± 0.24
11	1.01 ± 0.12	0.75	0.75 ± 0.11	0.75	0.80 ± 0.13	1.25	1.32 ± 0.14
12	1.13 ± 0.06	0.75	0.90 ± 0.07	0.75	0.88 ± 0.07	1.25	1.22 ± 0.09

TABLE III
SUBJECT TESTING WITH PREFERRED CHOICE OF SENSORY FEEDBACK

ID #	Control	First Trial			Second Trial		
	Ratio mean ± SD	Feedback	Target	Ratio mean ± SD	Feedback	Target	Ratio mean ± SD
1	1.06 ± 0.03	Visual	1.5	1.22 ± 0.09	Visual	0.5	0.71 ± 0.10
2	1.01 ± 0.11	Visual	1.5	1.21 ± 0.08	Visual	0.5	0.81 ± 0.11
3	1.13 ± 0.10	Audible	0.5	0.87 ± 0.12	Audible	1.5	0.90 ± 0.10
4	1.03 ± 0.04	Visual	0.5	0.65 ± 0.09	Visual	1.5	1.24 ± 0.08
5	1.18 ± 0.04	Visual	1.5	1.43 ± 0.15	Visual	0.5	0.62 ± 0.15
6	1.01 ± 0.10	Audible	0.5	0.59 ± 0.13	Audible	1.5	1.36 ± 0.25
7	1.04 ± 0.02	Visual	1.5	1.36 ± 0.22	Visual	0.5	0.64 ± 0.10
8	1.12 ± 0.08	Vibrotactile	0.5	0.96 ± 0.17	Vibrotactile	1.5	0.89 ± 0.15
9	1.08 ± 0.08	Vibrotactile	1.5	1.38 ± 0.39	Vibrotactile	0.5	0.96 ± 0.14
10	1.01 ± 0.06	Visual	0.5	1.11 ± 0.32	Visual	1.5	1.29 ± 0.19
11	1.01 ± 0.12	Visual	1.5	1.27 ± 0.28	Visual	0.5	0.69 ± 0.31
12	1.13 ± 0.06	Vibrotactile	1.5	1.30 ± 0.13	Vibrotactile	0.5	0.75 ± 0.13

feedback system showed that it did not. This corresponds to the results of the posttesting usability surveys, in which test subjects expressed difficulty in understanding and following the cues given by the audible system. In addition, a larger than expected variance was found in the gait ratios of the control tests (see Fig. 7) as compared to published standard [31]. This larger deviation could be a result of the implementation and weight (9 oz) of the microcontroller boxes on the subjects' ankle.

The results of the preferred method subject tests correlated the findings of the initial subject tests, in that the preferred method of feedback for each subject was successful in modulating their gait (Table II). The majority of the subjects preferred the visual feedback system, with seven choosing it, three choosing vibrotactile, and two choosing audible; therefore, statistical results for preferred feedback are only available for visual feedback. A posthoc power analysis was performed to verify the strength of the statistical analyses. The statistical power was above 0.97 for all visual tests and the initial vibrotactile and audible tests with a low gait asymmetry.

VII. DISCUSSION

The ARTISTIC system was successful in introducing a gait asymmetry in the subjects walking pattern, despite an extremely short training process compared to what would be considered normal during a gait rehabilitation program. This result suggests that this system could be used for assistive healthcare to positively adjust the gait of a rehabilitative patient with relatively little specialized training. Such rehabilitative use was shown to be possible through the easy and modular application of the ARTISTIC system for subject testing, with no specialized equipment or environment needed. This validates the use of the ARTISTIC system, as well as its strengths with respect to ease of use and inexpensive implementation. With an approximate prototype cost of US$225, it is an economical alternative to the more expensive options currently available. The high preference of the testing subjects for use of the visual feedback system, as well as the feedback received from the usability survey suggests that it was the most intuitive form of feedback for them to use. While this does not necessarily reflect poorly on the audible and vibrotactile feedback methods, it can be concluded that further work should be done to improve the ease of use for the other two system components, which were shown to have promise for a high level of effectiveness in influencing the gait of the test subject. Due to the small number of subjects who chose the audible and vibrotactile feedback as their preferred method, a future study with a greater amount of people will need to be performed, so as to provide an acceptable sample size for statistical analysis. From the preferred method testing, it was shown that the sensory feedback was capable of inducing large gait ratio abnormalities within each subject test. These resultant gait ratios, while large, did not quite reach the target offset in most of the tests. This result correlates with the earlier findings from the LEAFS system [5], that large permanent gait changes must be made gradually. In addition, the research performed on the LEAFS system showed a significant change in gait using an identical audible feedback method [5], which was not even statistically significant during trials using the ARTISTIC system. This further validates the possible use of the ARTISTIC system in rehabilitative training in addition to traditional clinical methods, and the importance of continuing to improve the individual feedback methods.

This initial study involved a relatively small subject pool, but still produced verification and results that built upon those from the previous LEAFS system. A posthoc power analysis was performed to evaluate whether the subject size was sufficient to avoid the possibility of a false positive when using the *t*-test; this was true for all of the visual feedback results. These initial testing results demonstrate that the ARTISTIC system performed as designed, and identified specific areas to target for improvement. Testing with larger numbers of subjects is planned in the future, particularly with subjects drawn from patient populations relevant to ARTISTIC system. Further system improvements include modifying the vibrotactile and audible feedback components to provide a more intuitive sensory experience. One of these improvements includes the possibility of mounting vibromotors and/or buzzers in each of the microcontroller boxes to target the feedback to each side of the user.

Another long-term goal is the incorporation of the power supply, microcontroller, and wireless transceiver into the insole. This would be simpler for users to install and use, and would reduce the amount of connecting wires and need for ankle mounting. Because the reduced power requirements associated with the ZigBee wireless protocol (compared to Bluetooth) are highly desirable, the use of ZigBee will be investigated, particularly as it becomes more widely available in smartphones. Previous versions of the insole sensing system were limited by their data rate to a maximum resolution of stance time measurement of 8.8 ms, thus, introducing a source of error into the data measurement [5]. The revised ARTISTIC system is capable of sensing and transmitting data at 1000 Hz, which corresponds to a decrease in the measurement resolution to 1 ms, thereby increasing the accuracy of the system. Another source of error is the algorithm used for detecting heel strike and toe off. Due to different influencing factors, the gait patterns of the user can change substantially, thereby requiring a robust and flexible algorithm to accurately capture gait data under all circumstances. While we have demonstrated that the threshold algorithm used here works well with multisensor insoles [35], a future study to verify the accuracy of the system against the current industry standard would be valuable for validation. It is also anticipated that future iterations of the system will include greater numbers of sensors, and the capability to do so has already been built into the current version. A potential weakness with the ARTISTIC system can be argued that it only treats the symptoms exhibited by patients with gait abnormalities, rather than the underlying physiological causes. However, as stated previously, the current methods for addressing a gait abnormality in a clinical setting are to establish a diagnosis, and then prescribe a treatment [2]. In this respect, the ARTISTIC system can be used both as a diagnostic tool to gather gait data away from the clinic, as well as a subsequent treatment device. The strength of the system therein lies in its versatility and inexpensive implementation at many different levels in the rehabilitative process. From these positive initial results, the next step is to use the ARTISTIC device in a participant study to determine its ability to positively rehabilitate subjects with gait abnormalities. These refinements and changes will serve to improve the system, and result in a valuable tool for wearable and independent gait feedback.

VIII. CONCLUSION

A real-time feedback system for gait modification and training was developed and tested on healthy human subjects. The system was determined to behave as expected, and was successful at inducing a gait abnormality in the subjects. The tests performed indicate that visual feedback is the most intuitive and easy to follow form of feedback, while vibrotactile and audible feedback need further refinement. Both visual and vibrotactile feedback were demonstrated to result in significant changes to gait asymmetry. The custom application that was written to control the system performed well, with the ability to provide valuable and effective gait feedback to the user. This system has potential for use in the rehabilitation and training of subjects who have undergone lower limb amputations, suffered from a stroke, or who have Parkinson's disease. In this way, it can serve as a supplemental rehabilitation method for use both in the clinic, and as a personal assistive healthcare device. To further develop this device, we will initially focus on further developing the auditory and vibrotactile feedback options, along with optimizing the power requirements, and shrinking the size of the associated electronics. Our next step is to use ARTISTIC in a larger study, to investigate its effects on persons with gait abnormalities. We are particularly interested in assisting persons with lower limb amputations to regain symmetric gait.

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