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SoleSound: Towards a Novel Portable System for Audio-Tactile Underfoot Feedback

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***Abstract*— This paper introduces the design of *SoleSound*, a wearable system designed to deliver ecological, audio-tactile, underfoot feedback. The device, which primarily targets clinical applications, uses an audio-tactile footstep synthesis engine informed by the readings of pressure and inertial sensors embedded in the footwear to integrate enhanced feedback modalities into the authors' previously developed instrumented footwear. The synthesis models currently implemented in the *SoleSound* simulate different ground surface interactions. Unlike similar devices, the system presented here is fully portable, and can therefore be utilized outside the laboratory setting. A first experimental evaluation indicates that the device can effectively modulate the perception of the ground surface during walking, thereby, inducing changes in the gait of healthy subjects.**

I. Introduction

Parkinson's disease (PD) is an idiopathic disorder that causes degeneration of the central nervous system (CNS). Some of the most debilitating symptoms of PD are the gait disorders: Parkinsonian gait and freezing of gait (FOG). The former results in small, shuffling steps. The latter is characterized by the inability to step for several seconds or longer. Furthermore, PD patients often suffer from weakened balance, which can lead to falls and serious injury. Currently, PD is clinically characterized using physician observation and camera-based motion capture systems. It is treated with drug-based therapies. Camera-based gait analysis can provide a more quantitative picture of gait disorders than clinician observation. However, camera-based motion capture systems are expensive and are not available at many clinics. Drug based therapies often effectively reduce Parkinsonian gait, but they seldom reduce FOG. Additionally, these therapies are not effective for all patients and their effectiveness often lessens over time, requiring that increasingly large doses of drugs be used.

Because of the shortcomings of current diagnosis and treatment options available for PD patients, researchers have developed wearable gait analysis [1]–[3] and sensory feedback devices [4]–[13] to be used in lieu of or in conjunction with traditional drug-based therapies. The former provide clinicians with detailed information about gait at a fraction of the cost of camera-based systems, even though they are usually less accurate. The latter are intended to provide patients with auditory, visual, or vibrotactile feedback (or combinations thereof) to help regulate their gait and balance and prevent falls. Early studies by Taut et al. [14], [15] unveiled the potential of auditory cueing in improving spatio-temporal parameters of gait in patients affected by various neurological disorders (stroke, PD, TBI). In a previous work, [16] the authors showed that concurrent audio-haptic feedback can effectively substitute visuohaptic feedback in favoring subjects' motor adaptation to an altered gait pattern. More recently, researchers have investigated *continuous audio-tactile feedback* produced by sonification engines (e.g., ecological feedback). Compared to *discrete feedback*, the latter can convey a wider range of information, and is thought to induce stronger motivational and emotional effects which may be beneficial for patients [17]. There is evidence that the rendering of different ground surface compliances through sonification of footsteps [10], vibrotactile feedback [18] and combination thereof [12] can alter the gait of healthy subjects, suggesting that such approaches can be transferred to the clinical setting. In a 2012 study, Rodger et al. tested a system that used force plates and motion capture to sonify gait with PD patients and found that it reduced variability in gait [4].

Following pioneering designs by Paradiso and colleagues [1], [2], a wide range of wearable gait analysis and feedback devices were developed, for both VR applications [6], [10], [12] or for medical applications [8]. Our group recently developed the PDShoes, a pair of water shoes outfitted with piezo-resistive sensors and vibrotactile motors [7]. In a 2013 study, Winfree et. al. showed a positive therapeutic effect of the PDShoes on a group of PD patients with FOG [19].

Existing instrumented footwear capable of synthesizing audio-tactile feedback in real-time rely on an external host-computer to generate the feedback, which is then sent back to the user through wired [10]–[13] or wireless [6], [13] connections. This limits the use of such footwear to the laboratory setting, and requires the constant assistance of a specialist. Fully portable systems, on the other hand, are currently limited to *discrete* feedback modes (e.g., vibration pulses or auditory alarms) [3], [8], [9], [19] which, although immediate to understand, can only convey simple information to the user. Additionally, most existing devices provide either auditory or vibrotactile feedback, thus not leveraging the benefits of multimodal feedback in terms of intersensory facilitation, response amplification, and reduction of cognitive load [17].

In this paper, we present the design and first experimental validation of the *SoleSound*, a novel wearable gait analysis and sensory feedback device targeted at PD patients. The

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device builds on the earlier work of the PDShoes, while also introducing some novel features in the field of instrumented footwear, such as the possibility to synthesize audio-tactile feedback in real-time with a fully portable system.

II. System Description

The uniqueness of *SoleSound* lies in carrying onboard all logic required for synthesizing continuous audio-tactile feedback in real-time, based on the readings of piezo-resistive and inertial sensors embedded in the footwear. Fig. 1 illustrates the design of SoleSound. The system consists of two footwear units and a belt unit. Each footwear unit measures pressure under the foot and kinematic data of the foot. These data are sent wirelessly to a portable single-board computer attached to the belt, where the audio-tactile feedback is generated in real-time and converted to eight analog signals - four per leg - by a sound card. A pair of thin stereo audio cables - similar to the ones used in headphones - carries the analog signals from the waist to each foot, where they are amplified and fed to vibrotactile transducers and loudspeakers.

A. Footwear Sensors

Four piezo-resistive force sensors (FlexiForce by Tekscan, Inc., South Boston, MA) are attached to the sole of each sandal (Teva Jetter, Deckers Outdoor Corp., Goleta, CA): underneath the calcaneous, the head of the 4th metatarsal, the head of the 1st metatarsal, and the distal phalanx of the hallux. During walking, these signals peak in sequence as the center of pressure in the foot moves from the heel to the toe, thus allowing identification of the sub-phases of stance (Fig. 2-A). The signals are digitized by a 10bit ADC and sent to the belt computer through a XBee Module (Digi International Inc., Minnetonka, MN). A 9-degree-of-freedom (DOF) inertial measurement unit (Razor IMU, Sparkfun Electronics, Boulder, CO) is mounted on the back Velcro strap of the sandal (Fig. 2-C). This unit features an on-board microcontroller that can be programmed with custom code. Linear acceleration of the heel and Yaw-Pitch-Roll angles estimated by an Attitude and Heading Reference System (AHRS) based on Direction Cosine Matrix (DCM) are sent to the belt computer at 35Hz through a second XBee module.

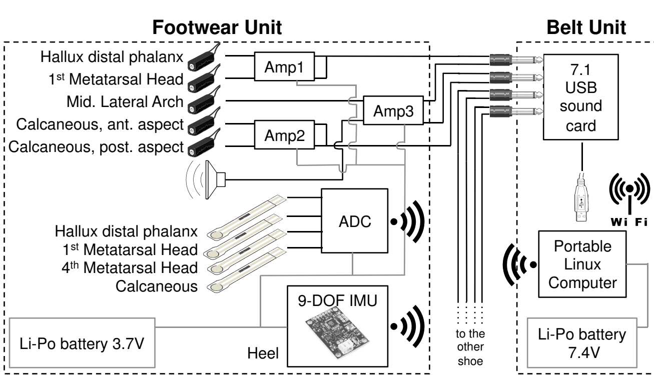

Fig. 1. System layout

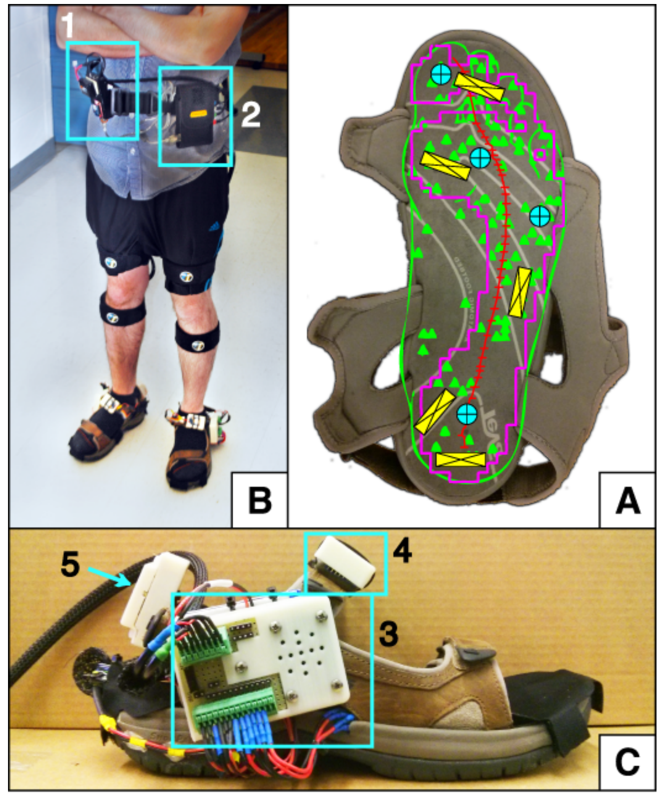

Fig. 2. (A) Nominal locations of the actuators (yellow rectangles) and of the piezo-resistive sensors (cyan circles). Shown in green is the map of the cutaneous mechanoreceptors in the foot sole [20]. The magenta outline illustrates the areas where the highest pressures are expected during walking, and the red curve shows the path of the center of pressure. (B) Subject wearing the belt unit, consisting of: (1) single-board computer, battery pack and Xbee module and (2) USB sound card. (C) Close-up of the shoe unit, showing: (3) the amp box, loudspeaker case and shoe battery; (4) ADC and Xbee module; (5) IMU and Xbee module.

B. Belt Unit

The single-board computer (BeagleBone Black, BeagleBoard.org Foundation, Richardson, TX) that attaches to the user's belt is powered by a small Li-Po battery that fits on the top of its enclosure. It hosts the coordinator of the multi-node wireless network in one of its Universal Asynchronous Receiver/Transmitter (UART) ports. A Linux distribution (Ubuntu 13.04, Canonical Group Limited, London, UK) runs on the BeagleBone Black (BBB), which operates in headless mode.

The open source real-time dataflow programming environment, Pure Data[1], which manages the audio-tactile footstep synthesis engine, is automatically loaded at startup. This software also performs data-logging of pressure data and kinematic data on a microSD card. The experimenter can optionally modify the feedback parameters by sending string commands through a TCP socket. The ethernet port embedded in the BBB operates wirelessly through a Mini Wireless WiFi Bridge. A USB sound card (StarTech.com USA LLP, Ohio) attached to the belt converts the audio data stream into eight independent analog channels. Two

[1]pd-extended v.0.43, source code available at: http://puredata.info/

pairs of stereo cables, both bundled inside thin PET cable-sleeving that attaches to the wearer's thighs and shanks, carry these signals to custom-made amplifier boxes mounted on the lateral-posterior side of the sandals (Fig. 2-C).

Unlike existing devices, which feature either wired or wireless connections between the footwear and the computer running the synthesis engine, the SoundSole utilizes a *hybrid configuration*, namely, input data are sent to the audio-tactile feedback engine wirelessly, while output signals are delivered to the transducers through cables. In general, wired connections are less prone to data loss and may reduce latency, however, they are less suitable for wearable devices. Specifically for the SoleSound, the cable sleeving routed through the legs does not noticeably restrict the wearer's motion. The wireless network solution adopted for the input data makes the SoleSound a *modular system*: additional input sources (e.g., inertial sensors) can be added in the future with minimal additional programming. Thus, the modified device could be used to measure the movements of the full leg and to explore new feedback strategies based on these measurements.

C. Actuation

Three 2-Channel audio amplifier boards (3W per channel) drive a loudspeaker mounted inside the amplifier box and five vibrotactile transducers embedded inside the sole of the sandal (Haptuators Mark II, Tactile Labs, Montreal, Canada). These actuators have a large nominal bandwidth (90 to 1000 Hz) and can be driven as loudspeakers.

Most existing instrumented shoes use headphones to convey auditory feedback [3], [4], [10], [11], [13], [18]. While this solution may increase a user's sense of immersion, it is obtrusive and does not resemble real walking conditions, where sounds are generated at foot level by the interactions between the shoe sole and the ground. Following the suggestion of Bresin et al., we therefore installed a small loudspeaker at foot level. Low-frequency sounds, which cannot be emitted by these small speakers, are provided by the actuators [12]. Based on the work of Kennedy and Inglis [20], the vibrotactile transducers were placed where the density of the cutaneous mechanoreceptors in the foot sole is highest, so as to maximize the effectiveness of the vibrotactile rendering (Fig. 2-A). In the current configuration, the two anterior actuators (hallux and 1st metatarsal head) are controlled by the same signals, as are the two posterior actuators (calcaneous). A LiPo battery attached to each sandal provides power to the amplifier box and to the sensors.

III. Real-time audio-tactile feedback engine

The auditory and plantar vibrotactile feedback, which is rendered by the footsteps synthesis engine presented in [21], simulates foot interactions with different types of surface materials. Although this kind of feedback does not generate the contact forces that take place in reality when subjects walk on a certain surface, several interactive audio-tactile experiments [11], [22], [23] have shown that it is effective in altering subjects' perception of the ground compliance, thereby affecting their gait patterns. The engine is based on a number of physical models: in the experiments described below, an impact model [24] was used to simulate a hard surface, whereas crumpling [25] and particle interaction [26] models were used to simulate an aggregate material. All physical models are controlled by an exciter signal simulating the impact force of the foot onto the floor, which is normalized in the range $[0,\ 1]$ and sampled at 44100 Hz [27].

Real-time control of the engine is achieved by generating the exciter signal of each foot based on the data of the inertial sensor and of the two piezo-resistive sensors placed underneath the calcaneous and the head of 1-st metatarsal. Based on the estimated orientation of the foot, the gravity component of the acceleration is subtracted from the raw acceleration. The resulting "dynamic" acceleration and the pressure values are normalized to the ranges $[-1,\ 1]$ and $[0,\ 1]$, respectively.

The exciter corresponding to a single step is modulated by the contribution of both the heel and the forefoot strikes. The two contributions consist of ad-hoc-built signals that differ in amplitude, attack, and duration. This allows us to simulate the most general case of a step, where the impact force is larger at the heel strike than at forefoot strike. These signals are triggered at the rise of the two pressure signals during a footfall (Fig. 3), when the first derivative of each normalized pressure value becomes larger than a predefined threshold. To render the intensity with which the foot hits the floor, the approach described in [27] was followed. The amplitudes of the exciter signals were modulated by the peak value of the L_1-norm of the acceleration vector measured between two subsequent activations of the calcaneous pressure sensor (Fig. 3).

The same signal was used for both the auditory and tactile feedback in order to mimic the real-life scenario, where the same source of vibration produces acoustic and tactile cues.

IV. Experimental validation

A. Protocol and data analysis

Three healthy male adults (age 22.5 ± 3.7 years, height 1.70 ± 0.13m, weight 65.4 ± 13.9kg) from our research group volunteered for this experiment, designed as an initial proof of concept validation of SoleSound. The goal of these tests was to assess whether or not the rendering of different ground surface compliances through audio-tactile underfoot feedback can alter the natural gait pattern of young healthy subjects.

A 6m long and 2.3m wide rectangular circuit was traced on the floor of the laboratory with red tape, and subjects were asked to walk approximately along this track in a counter-clockwise direction, while wearing the instrumented sandals. Reflective markers were placed on the subjects' feet and shanks to measure ankle plantar/dorsi-flexion angle and the kinematics of the feet. A rail-mounted motion capture system with 8 cameras (VICON Bonita 3) was used to track the markers at a sample rate of 100Hz. The protocol consisted of three 3-minute-long sessions (Fig. 4): the *Baseline*

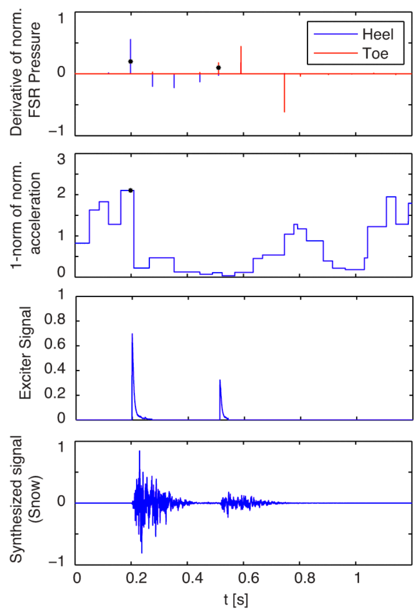

Fig. 3. Feedback generation process for a step. Top plot: time derivative of the normalized pressure values underneath heel and toe. Black asterisks indicate triggering events. Second plot: L1-norm of dynamic acceleration. Black asterisks indicate the maximum acceleration before triggering of the heel. Third plot: exciter signal scaled in amplitude. Bottom plot: synthesized signal simulating snow.

session, during which the feedback was disabled; the *Hard Wood* session, during which the feedback engine simulated a hard surface, and the *Deep Snow* session, during which an aggregate material was rendered. After session *Hard Wood* and session *Deep Snow*, 90 second-long sessions with no feedback were included to analyze potential after-effects (*AE*) of the audio-tactile feedback. Subjects were instructed to walk normally (without looking down at their feet) and they were not informed about the types of simulated walking surfaces. None of the subjects had previous experiences with instrumented footwear.

In this paper, we present results from the *Baseline*, *Hard Wood* and *Deep Snow* sessions, restricting the analysis to the last 90 seconds of each session. We hypothesized that subjects' gait would be affected by the four 90-degree turns that took place within each lap: for this reason, only the steps that fell inside a 3.2m long, straight-line segment centered in each of the long sides of the rectangular circuit were post-processed. In this way, subjects had 2 to 3 steps [28] available to reach a steady-state gait after a right-angle turn, or decelerate prior to a turn. The reference straight-line segments were also marked on the floor.

Stride time (T_{str}), normalized swing period (*SWP*) and normal ground reaction force (*NGRF*) at initial contact (IC) were estimated from the readings of the piezo-resistive sensors. T_{str} was defined as the time elapsed between two subsequent peaks of the heel signal. *NGRF* was defined as the peak value of the heel signal over the gait cycle. Step length (*STPL*) was computed as the projection of the horizontal displacement of a heel marker onto the plane of progression between IC of one leg and the subsequent IC of

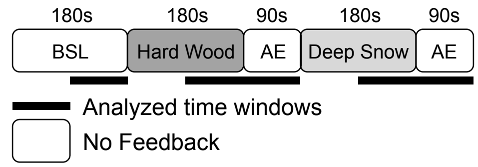

Fig. 4. Experimental protocol.

the contralateral leg.

Mann-Whitney tests were conducted separately for each subject, to check for significant ($\alpha = 0.05$) differences among the sessions. Bonferroni-Holm correction was applied to control the familywise error rate. In this preliminary study, gait was assumed symmetrical and therefore metrics computed from the left and right legs were averaged prior to the analysis. The readings of the piezo-resistive sensors were normalized on the peak values measured on each foot during the *Baseline* session.

B. Results

In *Deep Snow* mode (aggregate material, soft simulated compliance), the audio-tactile feedback significantly decreased cadence with respect to the baseline gait, resulting in increased T_{str} (Fig. 5). The magnitude of the normal ground reaction forces at initial contact - as estimated by *NGRF* - increased as well, compared to baseline values (Fig. 6), whereas step length decreased significantly (Fig. 7). All these changes were consistent across the three subjects. Interestingly, two subjects also showed a significant reduction of *SWP* (Fig. 8).

Results were more mixed for the simulated hard surface (*Hard Wood*). While T_{str} significantly increased in all subjects, step length showed decreasing trends, but changes were significant for subject 3 only, the other results being close to significance. Additionally, this mode significantly altered *NGRF* in all three subjects; however, while subjects 2 and 3 reduced the impact force, an opposite effect was found in subject 1.

Step height and range of motion of ankle plantar-dorsi flexion were also investigated. Even though both variables showed a decreasing trend from *Baseline* to *Hard Wood*

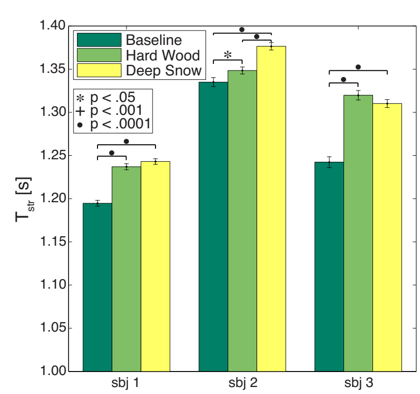

Fig. 5. Average stride time. Error bars indicate ±1SE. Reported are the naive *p-values* deemed significant by Bonferroni-Holm's method.

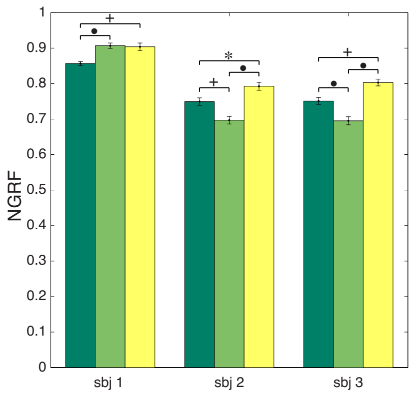

Fig. 6. Normalized impact force at IC. Error bars indicate ±1SE.

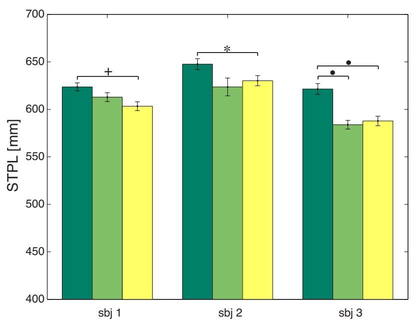

Fig. 7. Average step length. Error bars indicate ±1SE.

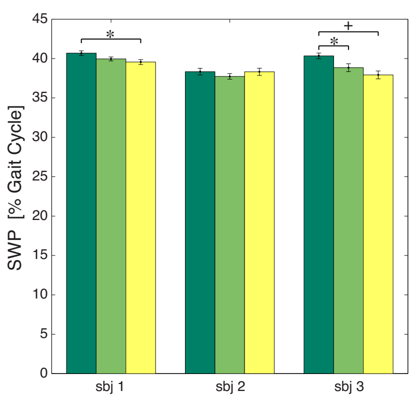

Fig. 8. Average swing period. Error bars indicate ±1SE.

and from the latter to *Deep Snow*, none of these differences reached significance and therefore they are not reported here.

Significant differences between the two feedback modalities were detected in *NGRF*: both subjects 2 and 3 showed smaller impact forces when the rendering of the hard surface was active, compared to when the rendering of the aggregate material was active.

C. Discussion

Overall, these results suggest that ecological underfoot audio-tactile feedback may significantly alter the natural gait cycle of young healthy subjects. Between the two tested feedback modes, the aggregate material was more effective in impacting the user's gait, especially in the variables *STPL* and *SWP*. This is in accordance with the results presented in [10] in the context of ecological sonification of footsteps. Unlike in that study, however, in this work significant alterations of subjects' natural step length and stride time were detected for both the harder and the softer simulated surfaces, which might indicate that concurrent auditory and vibrotactile ecological feedback are more effective than auditory feedback alone in impacting subjects' gait. This observation is also in accordance with findings by Visell et al. on the importance of plantar vibrotactile stimuli in influencing a walker's perception of the floor compliance [18].

Results on impact forces at IC suggest that opposite effects can be evoked on the users' gait when switching from the rendering of a hard surface to the rendering of a compliant one. To the best of the authors' knowledge, this is the first study on ecological, underfoot, audio-tactile feedback to report a decrease in the peak ground reaction forces at IC induced by a simulated hard walking surface and a corresponding increase induced by soft walking surface. Similar previous studies found no significant effects of the type of simulated surface on any of the walking parameters [12]. One possible reason for this result is the type of feedback engine utilized in this study, which modulates the feedback intensity based on an estimation of the ground reaction forces at IC obtained from inertial sensors mounted in the back of the footwear. This distinctive feature recreates the relevant auditory and tactile properties of foot-ground interaction in a more realistic fashion, and might have contributed to the illusion of walking on the specific simulated surface, at the behavioral and conscious levels.

At IC, a transfer of momentum occurs between the foot and the walking surface. The contact force equals the rate of change of the momentum: if the ground is compliant, relatively large displacements are allowed underneath the foot before the heel comes to a stop and the duration of the impact increases, thereby reducing the contact force [29]. Our results on the peak impact force across two different simulated surfaces showed an opposite trend, with higher (lower) contact forces recorded when the simulated compliant (hard) surface was active. Since the magnitude of the impact force in overground walking also depends on the subject's walking pattern (e.g., magnitude and direction of the velocity of the calcaneous prior to the impact), which subjects naturally adapt based on proprioception, type of walking surface and shoe insole material [30], it is possible that the illusion of a compliant walking surface induced higher impact speeds on subjects, which resulted in increased impact forces, given that the *real* walking surface remained the same in all sessions. Similar reasoning would also explain the lower impact forces measured when the hard surface was rendered.

V. Conclusion

This paper presented the design of SoleSound, a novel instrumented footwear capable of delivering audio-tactile underfoot feedback to the wearer by means of a real-time feedback engine informed by the readings of inertial and piezo-resistive sensors installed at the feet. Unlike existing designs, the prototype proposed here is fully portable. Five vibrotactile actuators embedded in each sole enable spatialization of the feedback, and a hybrid wireless-wired architecture makes the system modular, allowing future integration of additional wireless sensors to monitor the movements of the full leg.

Preliminary experimental results indicate that ecological underfoot feedback may alter the natural gait pattern of healthy subjects. However, whether or not these gait alterations can be modulated by the compliance of the simulated walked-upon surface is still an open question. While the magnitude of the impact forces at IC was larger for the soft surface than it was for the hard one, cadence and step length decreased in both cases. These strategies facilitate balance and can therefore be related to subjects' perception of walking upon an aggregate, compliant material. The lack of opposite effects for the hard simulated surface (e.g., increased step length) may be due to the difficulty in haptically rendering the impact between a hard sole shoe and the solid surface while the subjects actually wore soft sole sandals [23].

Limitations of the current study include the small sample size and the relatively short circuit used for the tests. Future experiments will include overground walking on a long hallway, and pilot testing on PD patients.

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