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An Integrated Multimodal Knee Brace Enabling Mid-Activity Tracking for Joint Health Assessment

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Abstract— **Developments in wearable technologies created opportunities for non-invasive joint health assessment while subjects perform daily activities during rehabilitation and recovery. However, existing state-of-art solutions still require a health professional or a researcher to set up the device, and most of them are not convenient for at-home use. In this paper, we demonstrate the latest version of the multimodal knee brace that our lab previously developed. This knee brace utilizes four sensing modalities: joint acoustic emissions (JAEs), electrical bioimpedance (EBI), activity and temperature. We designed custom printed-circuit boards and developed firmware to acquire high quality data. For the brace material, we used a commercial knee brace and modified it for the comfort of patients as well as to secure all electrical connections. We updated the electronics to enable rapid EBI measurements for mid-activity tracking. The performance of the multimodal knee brace was evaluated through a proof-of-concept human subjects study (n=9) with 2 days of measurement and 3 sessions per day. We obtained consistent EBI data with less than 1 Ω variance in measured impedance within six full frequency sweeps (each sweep is from 5 kHz to 100 kHz with 256 frequency steps) from each subject. Then, we asked subjects to perform 10 unloaded knee flexion/extensions, while we measured continuous 5 kHz and 100 kHz EBI at every 100 ms. The ratio of the range of reactance ($\Delta X_{5kHz}/\Delta X_{100kHz}$) was found to be less than 1 for all subjects for all cycles, which indicates lack of swelling and thereby a healthy joint. We also conducted intra and inter session reliability analysis for JAE recordings through intraclass correlation analysis (ICC), and obtained excellent ICC values (>0.75), suggesting reliable performance on JAE measurements. The presented knee brace could readily be used at home in future work for knee health monitoring of patients undergoing rehabilitation or recovery.**

Index terms: wearable technologies, knee health assessment, joint acoustic emissions, electrical bioimpedance, mid-activity joint health tracking

I. INTRODUCTION

Recent advances in wearable technologies have paved the way to enable continuous and ubiquitous health monitoring. Continuous health information can now be collected during a wide range of recovery and rehabilitation settings where traditional collection methods would be impractical. Additionally, the low cost of such wearable technologies improves their accessibility to a broader population.

Current diagnostic and monitoring technologies for assessing joint health are not easily affordable, inaccessible, and in some cases invasive. For example, knee arthroscopy is a common surgical operation that is widely accepted as the gold standard for evaluating the knee health [1]. Not only is the procedure cost-prohibitive, but it also requires sedation and post-operative recovery. Furthermore, there are commonly employed imaging techniques, such as magnetic resonance imaging, which are not easily accessible to rural communities and underserved populations [2]. In addition to these methods, pain questionnaires and physical exam maneuvers are commonly used. However, there are inconsistent reports in the literature regarding their accuracy, specificity and sensitivity [3], [4]. This raises questions about the objectivity and reliability of these methods. Most importantly, none of these methods provide the patient with real-time information about their joint health, especially during activity when they are most prone to an injury. Therefore, there is a need for affordable, non-invasive, and objective joint health monitoring technologies for both diagnostic and continuous health monitoring.

In the last decade, researchers have developed wearable technologies for joint health monitoring using new sensing modalities. For instance, joint acoustic emissions (JAEs) have been shown to contain valuable information about underlying joint health [5]. Moreover, electrical bioimpedance (EBI) spectroscopy has been used to detect changes in edema during injury recovery [6], as well as for mid-activity tracking [7]. Additionally, activity monitoring using inertial measurement units (IMUs) has been used to detect range of motion [8], joint stability [9], and joint kinematics [10]. Though each individual sensing modality has shown promising performance for joint health assessment, a multimodal fusion of captured information could offer greater insights than each modality individually. To this end, our group has recently developed a wearable, multimodal sensing system to monitor knee health [11]. This system can (1) capture JAEs from the knee, (2) perform EBI spectroscopy, (3) capture activity information, and (4) record skin temperature. While this system can provide multimodal sensing in a wearable form factor for use in clinical settings, it still requires a person to help fit the system on a user. This can reduce the repeatability of sensor placements and decrease the overall usability of the system.

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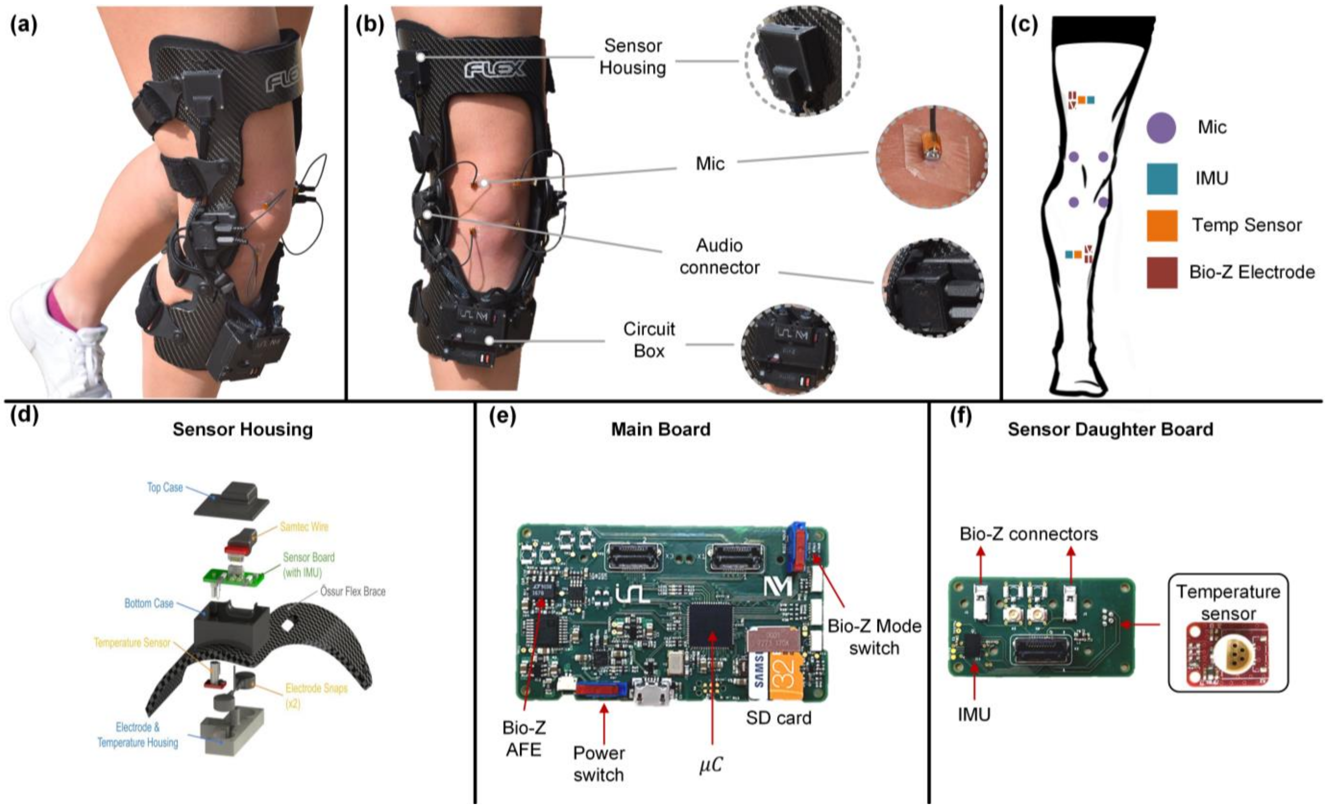

Fig. 1. Fully integrated smart knee brace. (a) Side and (b) front view of the brace. (c) Sensor placement. Exploded views of (d) circuit box and (e) sensor housing. The pictures of PCBs: (f) audio board, (g) main board, and (h) sensor daughter board.

Cable management also becomes an important issue with such modular designs [12]. Besides these usability aspects, this previous design was limited to full frequency sweep EBI measurements while subjects are stationary. However, recent reports demonstrated that real-time tracking of EBI during activity can provide important joint health information [13]. Therefore, it is necessary to develop an integrated wearable joint health assessment device that could be readily sent home with patients for capturing physiological data during activities.

II. TOOLS AND METHODS

A. *The Multimodal Knee Brace*

In this work, an integrated knee brace for joint health assessment is presented as in Fig. 1 (a-b). The system (1) captures JAEs using four microphones sampled at 46.875 kHz, (2) measures EBI, both full-sweep (5 – 100 kHz with 256 frequency steps, at every 10 seconds) and continuous high-low frequency measures (5 and 100 kHz at every 100 ms) for static and dynamic activities, respectively, (3) records inertial data with 100 Hz sampling rate, and (4) measures skin temperature at every second. The placement of the sensors is presented in Fig. 1 (c). Custom-designed PCBs were used to acquire and save all data, as shown in Fig. 1 (e-f). A commercially available hard, carbon-fiber knee brace was modified to fit all electronics using 3D-printed sensor housings as presented in Fig. 1 (a-b) and (d). The system was validated on a healthy population (n=9) by collecting data three times on two different days. After validating our system on a healthy population, we anticipate that this integrated smart knee brace could be used at home to monitor joint health during rehabilitation and recovery.

B. *Electronic Design*

1) *PCB and firmware design*

The system includes four PCBs: an audio board, a main board and two sensor daughter boards. The audio board was the same one used by our lab previously to sample four contact microphones at 46.875 kHz [11]. The main board was designed to implement EBI, and sample two IMUs and two temperature sensors synchronously with audio recordings as presented in Fig. 1 (e). We used the EBI system based on our group's previous work, utilizing an impedance analyzer integrated circuit (AD5933, Analog Devices Inc., Norwood, MA) connected to a custom analog front-end to interface with the body [11], [14]. The calibration scheme developed by Mabrouk *et al.* has been directly used in this study [14]. This scheme employs a multivariate linear regression algorithm to map theoretical and measured impedances of 20 test loads. Prior calibration of the system allows using calibration coefficients to convert measured tissue impedances to their actual values. A four-electrode configuration with Ag/AgCl gel electrodes is used to minimize the effect of skin-electrode impedance. The firmware was designed to do both EBI spectroscopy (5 kHz – 100 kHz with 256 frequency increments) at every 10 seconds, and continuous dual frequency (5, 100 kHz) EBI measurements every 100 ms. We directly incorporated the locations for the proper electrode placement that were suggested in a prior work as presented in Fig. 1 (c) [6].

For inertial measurements, we used the BMX055 (Bosch Sensortec GmbH, Kusterdingen, Germany) IMU, which is a three-axis accelerometer, gyroscope, and magnetometer. The current version of the system samples both accelerometer and gyroscope data. Specifically, two IMUs, one on the thigh and one on the shank, are employed to capture full range-of-motion of the knee as well as angular velocity and other relevant activity data as presented in Fig. 1 (c). To measure skin temperature, we used two TMP116 (Texas Instruments Inc., Dallas, TX) digital temperature sensors. The temperature sensors are located in-between EBI electrodes as presented in Fig. 1 (c). Both audio and main boards are powered by 500 mAh Li-ion batteries, and each board has an independent power switch that enables turning off the system while not in use to increase the battery life.

To accommodate the needs of an integrated brace, the design closely considered proper cable management. In our lab's previous design, the sensors were connected to the main board via floating cables that required user input and adjustment, making the device prone to user errors. With this new version of the brace, we designed sensor daughter boards as presented in Fig. 1 (b-f). The IMUs were directly placed on the daughter boards, and the temperature sensors were connected via latching circular connectors through drilled holes into the brace. Two electrode connectors were used on each daughter board to rigidly attach EBI electrode snaps on the brace. We also used a single connector for all sensors (IMU, temperature sensor and EBI electrodes) on each daughter board for their connection to the main board. This reduced the total number of cables in the design as well as helped with fixing them to the brace.

2) *Operation Modes*

The firmware was designed to have three different operational modes. The first mode is audio sampling where JAEs are recorded using the audio board, while activity and temperature data is provided by the main board. This first mode was implemented to capture JAEs during activity, such as knee flexion/extension. The second mode is full frequency range EBI spectroscopy, where the audio board is put in low power mode and the main board performs continuous EBI measurements at every 10 seconds while also sampling IMUs and temperature sensors. This second mode was implemented to capture full impedance spectrum that could provide information about both intra-cellular and extra-cellular content [14]. The third mode is continuous EBI measurements at 5 and 100 kHz at every 100 ms. As with the second mode of operation, the audio board goes into a low-power mode and the main board takes EBI measurements while sampling IMUs and temperature sensors. This third mode was implemented to capture the changes in the knee joint bioimpedance due to the movement of edema or inflammation caused by the pressure within the joint cavities during activities, such as knee flexion/extension and is based off of the prior work on ankle edema assessment [7]. Two binary switches were used to select the mode of operation, while another switch was used to initiate recordings.

C. *Mechanical design*

A commercial knee brace (Flex, Össur, Iceland) was leveraged in this design for three reasons: (1) the brace design provides sufficient space for hardware, (2) it is easy to don while maintaining good structural strength and stability, and (3) the company offers different sized braces for both legs. To improve the comfort of the brace, we attached foam material to the inside brace surface. While the soft texture of the foam material provided comfort, we observed the brace slipped during walking. To address this issue, we used cloth with a zig zag wave silicone pattern on the inside foam surface of the brace.

The main circuit box was printed using a black polylactic acid (PLA) material, and houses both the audio and main boards, as well as two batteries (LP-523334 3.7 V 500 mAh with PCM, Shenzhen PKCELL Battery Co., Ltd, Guangdong Sheng, China). The box is fixed onto the brace using thick double-sided adhesive tape. Similarly, the sensor housings were printed using black PLA, whose exploded views are presented in Fig. 1 (d). We drilled through the carbon fiber brace material to accommodate the temperature sensor connector passing through it, allowing the temperature sensor to measure the skin temperature directly. EBI electrode snaps are also connected to the daughter boards through these holes via small cables. The daughter boards are also fixed onto the brace using the thick double-sided adhesive tapes.

The cables between each daughter board and the main board were fixed onto the brace using zip ties along the brace. Latched connectors were used on each PCB to protect the electrical connections against pulling. Additionally, to minimize user interaction with the system, male to female audio connectors were mounted on the hinges. This ultimately minimized microphone cable length and prevented cables from floating along the brace. This also minimized user interaction with the PCBs, where previously applying stress on them through plugging and unplugging the microphones could damage the audio connectors. The microphones were attached to the skin on 2 cm from the medial and lateral sides of the distal patellar and quadriceps tendons using double-sided Elizabeth tape [15].

D. *Experimental setup*

Institutional Review Board (IRB) approval was obtained from Georgia Institute of Technology (Protocol Number: H20329) to evaluate the device on human subjects. We recruited 9 healthy subjects (2 female and 7 male, age = 26.1 ± 1.76 years, weight = 68.6 ± 9.8 kg, height = 175.0 ± 11.4 cm) and measured JAEs and EBI, with each subject providing a written consent. We tested the same medium-sized right knee brace throughout this study, and subjects were asked to don the brace by themselves without any help from a researcher. JAEs were measured on two different days and three times on each day to run intra- and inter-session consistency analyses. Subjects were asked to perform 10 unloaded knee flexion/extension cycles in each session (in total 6 sessions), and they were provided a supplementary video to help them keep a steady pace throughout the measurement [5]. EBI data was collected on a single day. For the full frequency sweep mode, subjects were asked to extend their legs on a flat surface at rest, and the data was collected for 60 seconds (six full frequency sweeps) to show consistency between sweeps. Additionally, subjects were asked to perform another 10 unloaded knee flexion/extensions cycles while continuous EBI measurements were taken.

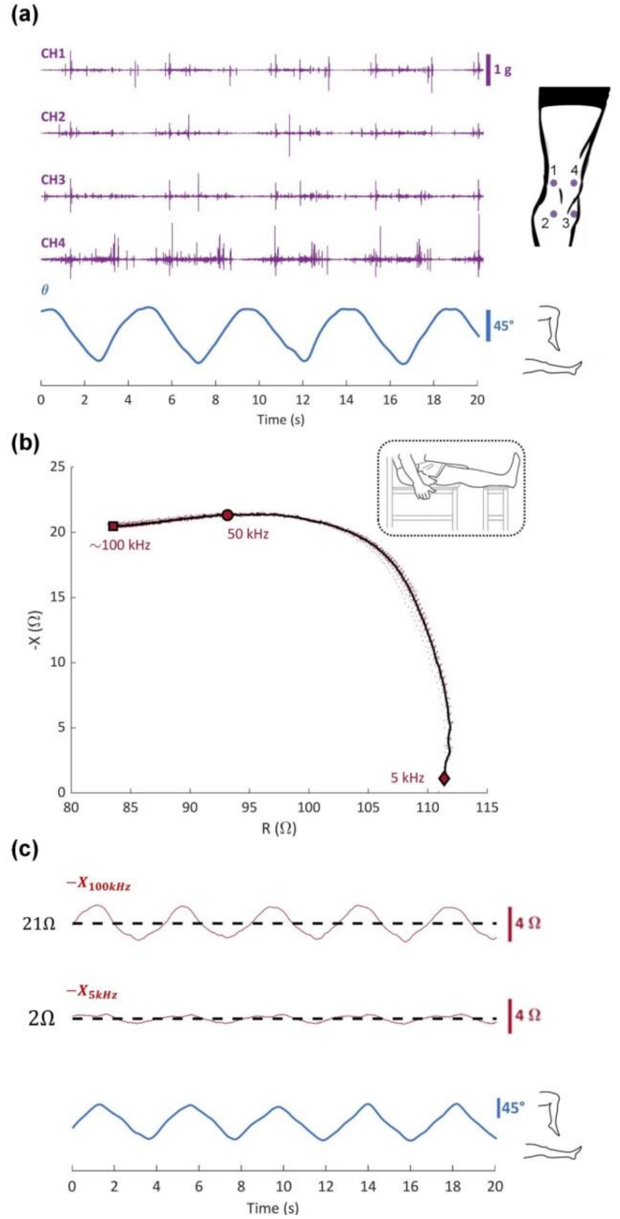

Fig. 2. Sample signals measured from one of the subjects. (a) Four channel JAEs synchronized with joint angle data. (b) Resistance versus reactance plot for different frequencies obtained through 6 full EBI frequency sweeps. (c) Reactance values measured through continuous EBI together with joint angle.

E. Signal Processing and Statistical Analysis

Following data collection, JAE recordings were bandpass filtered with 50 Hz – 5 kHz cut-off frequencies as recent findings showed relevant joint health information in JAEs in this frequency band [12]. Then, each recording was decomposed into flexion/extension cycles which were obtained through joint angle estimation using an algorithm presented by McGrath *et al.* based on IMU data [16]. We extracted 14 features from each cycle as these features were shown to be correlated with knee health [17]. Namely, these features are: spectral kurtosis, spread, centroid, decrease, entropy, flatness, roll-off point, skewness, slope and crest, harmonic ratio, arithmetic mean frequency, geometric mean frequency and zero crossing rate. We used a 40 ms window length with 90% overlap during feature extraction. The average of each feature value was calculated for each flexion/extension cycle, and each cycle was assigned a 14x1 feature vector representing their characteristics.

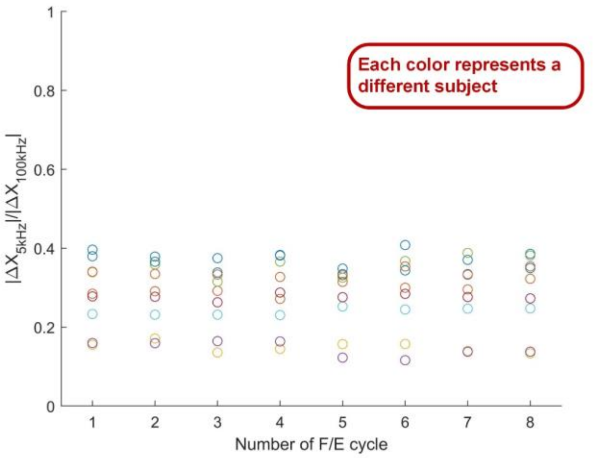

Fig. 3. The range ratio of 5 kHz and 100 kHz reactances for 9 healthy subjects through 8 knee flexion/extension cycles.

To evaluate intra- and inter-session reliability, intra and interclass correlation coefficients (ICC) were calculated where each flexion / extension cycle, or feature vector, acts as a measurement where every feature is a "rater." In literature, ICC values above 0.75 are accepted as excellent; therefore, we decided to use an ICC value threshold of 0.75 as the threshold of consistency for both inter- and intra- session analyses with a confidence interval of 95% [18].

The raw EBI data from each subject are calibrated with the scheme proposed by Mabrouk *et al.* [14]. For full sweep mode, the ensemble average of six sweeps were calculated for each subject. For continuous mode, calculated resistance and reactance values were plotted with respect to time.

III. RESULTS AND DISCUSSION

The system was characterized using the same methods described by Teague *et. al.* [11], and similar system specifications were obtained since no major hardware or firmware changes were done to the electronics. We conducted a drop sample test while a subject was wearing the brace for four hours, and no data packet drops were observed in either operation modes. We plotted the signals measured from one of the subjects in one session in Fig 2. Repeated patterns of JAEs were observed at consistent joint angles as presented in Fig. 2 (a). This performance is in accordance with our prior work [11]. The full sweep EBI characteristics are presented in Fig. 2 (b). We observed consistent EBI characteristics during six sweeps, while the standard deviation of measured impedance was less than 1 Ω from the ensemble average. Additionally, the impedance curve presents the expected behavior based on the Fricke-Morse bioimpedance model which is a common representation of the electrical characteristics of tissue using two resistors and one capacitor. The average skin temperature of this subject was measured as 28.9 ºC.

The continuous EBI measurements for a sample subject were presented in Fig. 2 (c). It was observed that the range of 5 kHz reactance was less than the range of 100 kHz reactance within each knee flexion/extension cycle. The ratio of low to high frequency reactance ($\Delta X_{5kHz}/\Delta X_{100kHz}$) during flexion/extension cycles for all subjects is plotted in Fig. 3. Note that we removed the first and last flexion/extension cycles from this analysis because some subjects could not perform these cycles at the correct pace. This reactance range ratio was found to be less than 1 for all subjects, which suggests a healthy joint based on our lab's recent work on ankle [13]. In that work, it was shown that the reactance range ratio should be greater than 1 for injured population during activity. This consistent result on a healthy population with a previous study suggests the potential of continuous EBI measurements for knee health assessment. With improved usability aspects of the brace, such as shorter donning time, better cable management, and more consistent sensor placement with all electronics integrated on a hard brace, mid-activity continuous EBI data can be captured in a broad range of daily and at-home settings.

For the repeatability of JAEs, we performed intra- and inter- session ICC analyses, and obtained ICC values greater than 0.80 and 0.86 for all features for all mics, respectively. Since all ICC values were greater than 0.75 for all features for both analyses, we concluded excellent reliability of JAEs with our smart brace [18]. In fact, this result also suggests that the brace introduces minimal characteristic noise or interference to acoustic measurements because each subject's JAE data has its own spectral and temporal characteristics.

IV. CONCLUSION

In this work, we presented an integrated wearable knee brace capable of recording JAEs, EBI, activity and skin temperature. The performance of the brace was presented through a proof-of-concept human subjects study, where reliable JAEs and EBI data were collected. The results of mid-activity continuous EBI measurements suggest potential use of the method for knee health assessment during activities. The easy-to-use design of the brace would help subjects use the device without the presence of any healthcare professional or researcher. The improved cable management and sensor placement would also improve data quality in uncontrolled settings. This new version of wearable joint health assessment system could be used in at-home settings for continuous knee health monitoring during rehabilitation and recovery.

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