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Soft Wearable Knee Brace with Embedded Sensors for Knee Motion Monitoring

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Abstract— **E-textiles have shown great potential for development of soft sensors in applications such as rehabilitation and soft robotics. However, existing approaches require the textile sensors to be attached externally onto a substrate or the garment surface. This paper seeks to address the issue by embedding the sensor directly into the wearable using a computer numerical control (CNC) knitting machine. First, we proposed a design of the wearable knee brace. Next, we demonstrated the capability to knit a sensor with the stretchable surrounding fabric. Subsequently, we characterized the sensor and developed a model for the sensor's electromechanical property. Lastly, the fully knitted knee brace with embedded sensor is tested, by performing three different activities: a simple Flexion-extension exercise, walking, and jogging activity with a single test subject. Results show that the knitted knee brace sensor can track the subject's knee motion well, with a Spearman's coefficient (r_s) value of 0.87 when compared to the reference standard.**

Long-term continuous monitoring of human motion can provide vital information that can be used to monitor recovery from sports injuries, stroke rehabilitation or even aid in the detection of early stage of Parkinson's disease [1]. Although current practice of visual inspection is able to identify joint motion abnormalities to a certain degree, clinicians prefer to identify, locate, and monitor abnormalities using quantifiable and accurate measurement systems over a continuous period of time [2]. Therefore, providing clinicians with crucial information on joint motion for activities of daily living (ADL) is essential, as it can help clinicians to detect physical lesions and provide early intervention for Parkinson's disease [3] or rehabilitation [4], [5].

The current approach for measuring of human motion can be achieved using non-wearable systems (NWS) or wearable systems (WS). Motion capture (mo-cap) and ground force plate sensors are some of the classic examples of NWS that provide highly repeatable and reproducible results [6], [7]. However, the measurements are usually taken in a controlled laboratory environment [8], [9] and require trained personnel to operate the devices, making them impractical for long-term joint monitoring and sustained rehabilitation treatment [10].

Next, inertial measurement units (IMUs) are the typical WS used in joint motion sensing. However, to estimate the joint motion, a minimum of two IMUs are needed to sense the limb's relative angular velocity and acceleration, which could obstruct user's movement during measurement [11], [12]. Besides, IMUs have an unavoidable drift issue that requires additional computational work to achieve accurate motion data [13], [14].

Recently, there has been tremendous interest in the development of soft wearable e-textiles for sensing applications [15]. Owing to their stretchable, breathable, light weight and soft texture, they serve as an excellent material choice for the development of soft sensors or even actuators that can be integrated into daily knitwear. For instance as piezoresistive sensors due to their highly elastic property and intrinsic resistance changes when undergoing strain [16]. These sensors have many advantages over existing NWS and IMU devices as they are lightweight, non-invasive and unobtrusive. This makes them more comfortable for patients, and also more practical for long-term motion monitoring [17].

However, most of the existing studies require such sensors to be attached to the user's clothing or substrate externally, making it prone to error if the sensor is displaced from its intended location due to manufacturing limitation [18], [19], [20]. To overcome this limitation, we developed a soft knitted knee brace with embedded sensors that can be knitted as a single piece using a computer numerical control (CNC) knitting machine.

I. CNC KNITTED KNEE BRACE & SENSOR CHARACTERIZATION

A. CNC Knitting Concept & Knee Brace Design

To create a knitted fabric, one or more yarns are formed into knitted loops that loop through existing loops [21], [22]. With CNC knitting machines, the action of each needle and yarn carrier is controlled individually, allowing us to vary the stitch patterns, yarn materials, and geometry of a single knitted object with minimal post-processing. This gives us the design freedom to create a multi-material wearable knee brace that seamlessly integrates the sensor and the garment.

In this paper, we designed a customized knee brace with the sensors embedded in it. The design of the knitted knee brace is shown in Fig. 1. It has three sensors embedded 5 cm apart, with the left and right sensors acting as redundancy sensors [25]. They help us to determine an appropriate location for the sensor to pickup electrical signal relative to the motion. The sensors are connected on one side to form a common ground. Other end of the sensors and the common ground are then connected to a circuit using thin

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metallic wires. The circuit schematic and the performance of the knee brace are discussed in Section II.

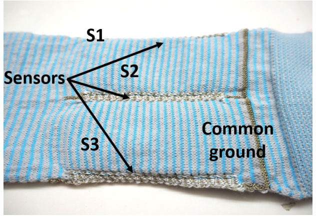

Fig. 1. CNC Knitted knee brace with embedded sensors.

B. Sensor Fabrication

Sensor is the key component of the knee brace. For sensor characterization experiments, 7 standalone sensors were knitted on a Shima Seiki MACH2XS153 WHOLEGARMENT® 15 gauge knitting machine. The sensor was knitted with alternating courses (rows) of electrically conductive silver-coated polyamide yarn (supplier: Statex, product: Shieldex® 235/36 dtex 2 ply HC+B) and nonconductive Tencel™ yarn (supplier: Lenzing AG, product: 15/1 siro spun) (Fig.2). The sensor was knitted using purl (garter) stitch pattern [23] and measured approximately 5x84mm in the relaxed state.

Since the sensor would be integrated within a knee brace, the sensor was knitted within a tube of single jersey (stockinette) fabric that alternated between 2 courses of nonconductive spandex covered yarn (supplier: Zhejiang Kangjiesi, product: 210D spandex with 2x75D polyester) and 2 courses of acrylic yarn (supplier: Miyama Tex, product: Guanti 2/32), as shown by the blue and white loops in Fig. 2. To pretension the sensor and prevent it from appearing wrinkled, the surrounding nonconductive fabric was knitted with twice the number of courses as the sensor so that the sensor would be stretched by the surrounding fabric. To make it easier to mount the sensors onto a experimental setup, the tubes were cut along the sides and the cut edges were overlocked to prevent unravelling.

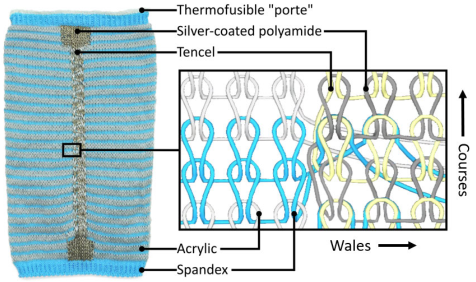

Fig. 2. CNC Knitted sensor with close-up showing yarns and stitch patterns. The spandex covered yarn is shown in blue and the acrylic yarn in white, constituting the surrounding fabric. The conductive yarn is shown in yellow and the non-conductive Tencel yarn in grey, forming the sensor.

C. Experimental Setup & Sensor Characterization

The experimental setup consists of two Extech (382260)-80W switching mode DC power supply and stepper motor from Oriental motor (Model AZM69AK). The first power supply provides a constant current across the knitted sensor and the second power supply provides a constant voltage to the load cell. The stepper motor is controlled by an Arduino Uno to stretch the knitted sensor at a specified speed along a linear stage, and the measured output voltage from the knitted sensor and the encoder data from the stepper motor were simultaneously recorded at 200Hz (5ms) using a real-time embedded evaluation board (National Instrument: MyRio). The complete experimental setup is shown in Fig. 3a.

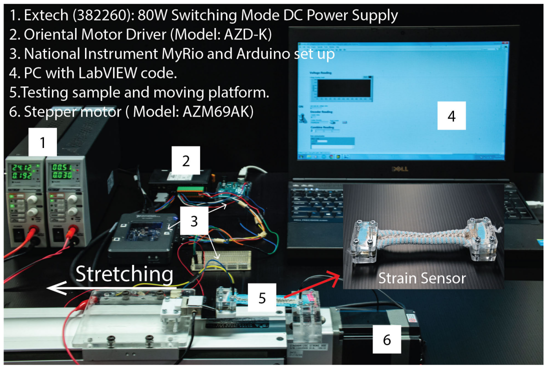

Fig. 3. (a) Experimental setup for sensor characterization, and (b) assembled strain sensor.

The interface for attaching the knitted sensor to the experimental setup is shown in Fig. 3b. It consists of two rectangular clamps attached to the ends of the sensor. The clamps were laser cut from a 5mm thick transparent acrylic sheet, and the knitted sensor was then secured using four socket screws and five connectivity pins to prevent the knitted sensor from sliding during the test. A small constant current of 30mA was supplied to the sensor through the connectivity pins and the output voltage was measured across the knitted sensor as its resistance changes under strain [24].

All tests were conducted using the automated experimental setup and the measured output voltage & encoder data were normalised according to the initial voltage $\varepsilon_v = (\frac{V_i - V_o}{V_o})$ and length $\varepsilon_x = (\frac{L_i - L_o}{L_o})$. V_o and L_o denote the initial voltage and length of the fabric prior to strain, and V_i is the voltage, and L_i is the length of the fabric at particular instance of time.

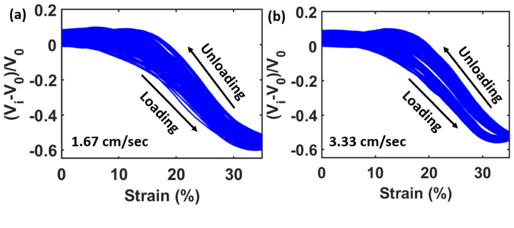

Fig. 4. Normalized voltage vs strain response of the sensor for 30 cycles of loading-unloading at (a) 1.67 cm/sec speed, and (b) 3.33 cm/sec speed.

Fig. 4 shows the response of the sensor to cyclic loading of maximum 35% strain at two different strain rates, stretched at a speed of 1.67 cm/sec and 3.33 cm/ sec for 30 cycles. Fig. 4a shows the response of the sensor from the third cycle onwards. As can be seen, the sensor shows hysteresis behaviour upon cyclic loading. Fig. 4b shows the response of the sensor when subjected to cyclic loading at 3.33 cm/sec speed.

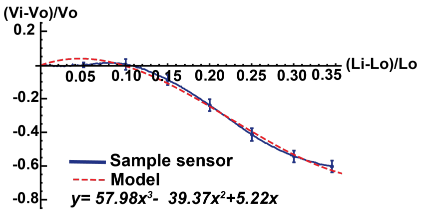

Fig. 5. The normalized voltage-strain relationship graph.

In this paper, we used a simplified cubic polynomial model to fit the sensor response. Fig. 5 shows the response of the sensor in blue (solid line) for fifth cycle when stretched at 3.33 cm/sec. The fitted cubic polynomial model is shown in red (dashed line).

II. KNEE BRACE PERFORMANCE & JOINT PARAMETRIZATION

The work described in this section was done as part of the preliminary efforts to standardise experimental steps and finalise the study protocol. As such, ethics review was not obtained at this stage. With the finalised study protocol, we are planning for a pilot study with recruitment of healthy subjects to evaluate the performance of the wearable sensor, and this is currently under review by the institutional review board. The fully knitted knee brace with embedded sensors is tested and its performance is evaluated on a healthy subject's left knee while performing three activities: a simple flexion-extension exercise of the knee, walking at 1.5km/h and jogging at 5km/h activity. All three activities were performed on the AMTI force plate treadmill for an approximate duration of 10-12 seconds.

The design of the electrical board and the circuit schematic diagram is shown in Fig. 6a and Fig. 6b respectively. We used three potential dividers in parallel to read the three sensor inputs. Teensy has two 12-bit analog to digital converters, allowing us to take readings with a resolution of up to 0.8 mV on each pin. Since the voltage in every node is 3.3V, we can use the analog reading at each pin to calculate the sensors' resistance using the following Eq.(1). Based on the output voltage reading from the three activities conducted, sensor S2 at the centre of the knee provided maximum strain compared to S1 and S3. As a result, S2 produced better signal compared to S1 and S3. Hence, it is used to compare with the reference standard.

$$R_{KS} = (V_{AI} \times 47\Omega)/(3.3V - V_{AI}) \tag{1}$$

To validate our knee brace measurement accuracy, we used a Vicon (Oxford, UK) system as the reference standard for comparison. A total of 15 reflective markers were attached to the subject's lower left extremity, and all three activities were recorded on nine motion-capture cameras. The motion data from the Vicon system was sampled at 100Hz, and the data from the knitted sensors were sampled at 6Hz. Both data sets

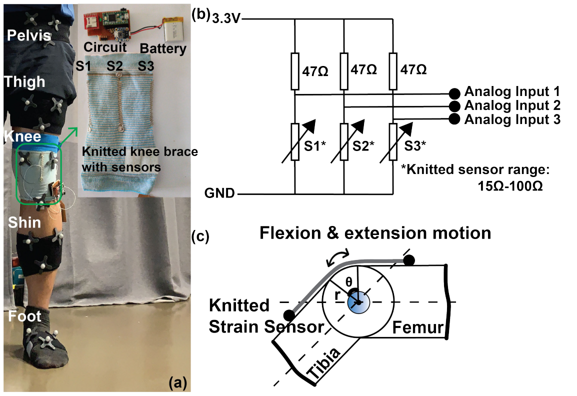

Fig. 6. (a) Design of the knitted knee brace and reflective markers, (b) electrical circuit schematic diagram and (c) pulley model schematic diagram.

were then processed in MATHEMATICA and the knee angle motion along the sagittal plane was compared. The coordinate locations of the 15 reflective markers were used to calculate the center of rotation (COR) and the revolute axis. For more information on the calculation, please refer to [26]. To relate the data collected from the electrical circuit to knee angular motion, we utilized the pulley model system shown in Fig. 6c. First, the strains were calculated from the measured voltage using the polynomial function model as shown in Fig. 5. Next, using the calculated strain and the subject's anthropometric radius, we obtained the knee angular motion using Eq. (2) along the sagittal plane.

$$L = r\theta \tag{2}$$

III. RESULTS & DISCUSSION

The comparisons between the reference standard Vicon and the knitted knee brace sensor (S2) for a simple flexion-extension, walking and jogging are shown in Fig. 7. The results obtained demonstrate that the knitted knee brace sensor can be used to monitor the knee motion along the sagittal plane. For the knee flexion-extension, the maximum peak error of 7.89° occurs at the peak of third cycle, as shown in Fig. 7a. During walking, the maximum peak error was 9.62°, shown in Fig. 7b. For jogging, the maximum peak error was 16.46°, Fig. 7c. To evaluate the wearable knee brace sensor accuracy, we also calculate the Spearman's coefficient r_s values for all activities. Two variables are considered to share a moderate monotonic relationship if their $r_s \geq 0.75$ [27], [28]. The individual r_s values for flexion-extension, walking and jogging were 0.92, 0.84 & 0.86 respectively and the average r_s was 0.87. These values demonstrate that there is a strong relationship between the knitted knee brace sensor and the reference standard.

The knitted knee brace thus demonstrates the ability to track the knee motion on the sagittal plane for walking and jogging activities with reasonable accuracy. However, there are still errors generated that are not entirely negligible. As can be seen, most of the error occurs during the stance phase for both walking & jogging trials. The angle difference during the stance phase is between 11.32°-29.35° and these errors could be due to the following reasons. First, the electrical

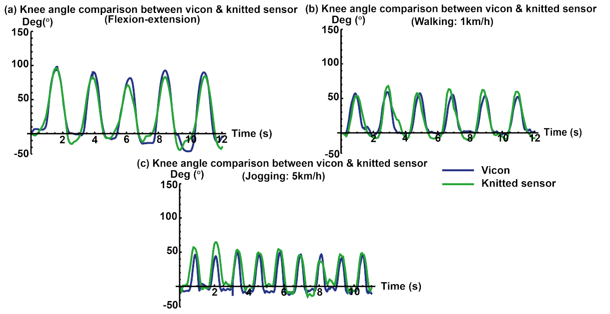

Fig. 7. Angle comparison between Vicon and middle knitted knee sensor for (a) flexion-extension, (b) walking (1.5km/h) and (c) jogging (5km/h).

board's low sampling frequency results in data loss and a lower resolution for comparison. Second, the model does not account for rate-dependent hysteresis and its effect on the sensor's electromechanical property during different operating speeds. Lastly, we noticed that the sensor may undergo compression as the knee is relaxed. The compression of the sensor may cause uneven contacts in the conductive fabric, resulting in a larger error during the gait stance phase.

IV. CONCLUSIONS

This paper presented a method to directly integrate sensing capability into a soft knitted knee brace. We have characterized the electromechanical property of our knitted sensor design and validated its usability by demonstrating that it can be used to track the knee motion along the sagittal plane for the three activities.

Future work will involve improving the existing knitted sensor design to achieve a better working range and sensitivity and improving the model by incorporating the strain-rate hysteresis effect. At the garment design level, we can prestress the knee brace which can enhance the sensor-skin contact and minimize errors during the stance phase in the gait cycles. Lastly, we will increase the number of test subjects to evaluate performance of the knitted knee brace across multiple subjects, including subjects suffering with mobility health disorders.

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