Smart Brace for Continuous Monitoring of the Knee Joint

Team 20

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***Abstract*—Over 100 million people suffer from chronic knee pain and about 1 million are admitted to the ER for serious knee injuries. Since it is the most common injury in America, knee injuries are the most prominent cause of missing workdays and have led to some professional athletes losing a lot of money or their careers. To combat this, a smart brace was designed to continuously monitor the health of the knee joint by measuring the acoustics produced by the bones, muscles, and tendons of the user. These measurements are then stored in an app accessible to the user via their phone or computer. The recorded measurements can also be shared with the user's physician to reduce the number of doctor visits.**

I. Introduction

The human knee consists of four main components that are vital to determine knee health: Articular Cartilage, Meniscus, Femur, and Tibia (Figure 1). To prevent discomfort and maximize mobility, the Articular Cartilage is a slippery substance that covers the Patella to ensure that the bones rub smoothly against each other while in motion. Additionally, the Meniscus is a tough and rubbery cartilage located between the bones that acts as a "shock absorber" against sudden force and strain applied to the knee joint. With repetitive strain and age, the Articular Cartilage and Meniscus begin to deteriorate, causing bone-on-bone contact, which is the most common injury reported across all ages.

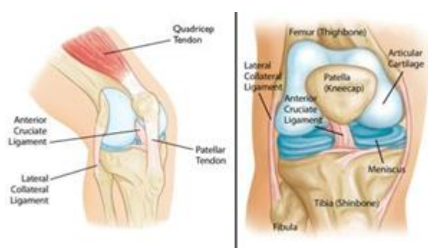

Figure 1: Internal view of the knee joint [1]

As the bones in the knee joint rub against each other, they produce sounds that relate to the quality of the joint that may not be audible to the human ear. These sounds are referred to as acoustic vibrations and can be measured as a periodic or irregular sound wave, depending on the type of motion. The main component of these sound waves that can be used to measure and monitor knee health is the amplitude of the sound wave. The amplitude correlates to the height of the sound wave and the higher the amplitude, the louder the sound. This correlation contributes to how the sounds from a knee joint can be monitored and measured for many issues. When the Articular Cartilage and Meniscus are in good condition, the friction between the Femur and Tibia is significantly reduced, resulting in a sound wave with a low amplitude. As these parts begin to atrophy, friction between the bones will increase, causing the amplitude of the soundwave to get higher and the volume to get louder. Large amounts of continuous friction in the knee joint increases the likelihood of injury and chronic pain.

Since most of the sound waves created by the knee are not audible to the human ear, the smart brace will utilize piezoelectric and MEMS sensors, which can measure the inaudible sounds of the knee so that the users and their physicians can keep track of their knee joint health to prevent future injuries or chronic pain. This application can also be used to monitor rehabilitation after surgery.

II. External Design

A. Sensor Placement and Knee Brace Design

The base design for the smart brace is a compression sleeve with modifications to help combat any environmental and occupational hazards that the user may encounter. The compressive nature of the sleeve allows the piezoelectric contact sensors to be in constant contact with the user's skin to ensure quality measurements. The material of the sleeve is a combination of spandex and soft fibers that increases comfortability and adjustability for the user.

The two piezoelectric contact sensors will be placed at the top and bottom of the kneecap to ensure that the sensor is in constant contact with the user's skin regardless of motion. The two airborne MEMS sensors will be placed on both sides of the kneecap which will allow the sensors to pick up any acoustics that penetrate the air when the knee joint is in motion. The sensors will be placed in mesh pockets on the inside of the sleeve along with some protective foam. There will also be a protective sensor package that will shield the sensors from environmental effects. (Figure 2).

Figure 2: Sensor placement on the knee brace

B. Sensor Package

Since sensors with high sensitivity parameters are used to measure the acoustics produced by knee joints, packages were designed using SolidWorks to protect the sensors and provide better functionality during usage (Figure 3). The sensor packages are made of ABS plastic and can be 3D printed due to the simplicity of the design.

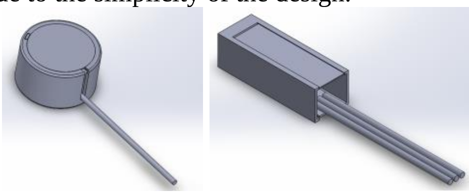

Figure 3: Sensor package for the piezoelectric sensor (left) and the accelerometer (right)

C. *Interface Material*

To hear and measure sound, the acoustic waves must propagate through a medium at a certain speed. This creates an acoustic impedance, which determines how well sound waves will travel through a medium. In the equation below, the acoustic impedance (Z) is equal to the speed of sound (c) multiplied by the medium's density (p).

$$Z = c * p$$

In this application, we have two different mediums that need to have similar impedances so that the sound waves can travel through with minimal reflection. The Intensity Reflection Coefficient (IRC) is used to calculate how much of the sound waves will be reflected. This value calculated from the equation below, determines how much sound will successfully penetrate both mediums and enter the sensors.

$$IRC = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

While the design of this device aims to ensure maximum contact between the user's skin and the contact sensors, air pockets between the two mediums may be created during use. Air has a very different impedance than skin, which will cause majority of the sound waves to be reflected and not reach the sensors. To solve this potential issue, an interface material is needed to help facilitate sound wave penetration so the sensors can measure the acoustics of the knee joint. For this application, PDMS is the best interface material to use since it has a similar impedance to skin.

III. INTERNAL DESIGN

A. *Airborne and Contact Sensors*

The piezoelectric contact sensors are used to measure vibrations from the knee joint though the user's skin. The airborne MEMS sensors are used to measure audible sound from the knee joint that penetrates the air.

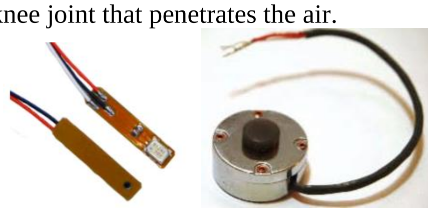

Figure 4: Airborne MEMS (left) and piezoelectric contact (right) sensors

B. *Bluetooth Module and ADC*

The Analog to Digital Converter (ADC) on the Arduino Uno will transform the voltage outputs of the airborne and contact sensors into digital outputs so that the Bluetooth Module can recognize the data. Wires will connect the sensors to the ADC pins of the Arduino Uno for the conversion of the outputs and connect the ADC output pins to the input pins of the Bluetooth Module Evaluation Board.

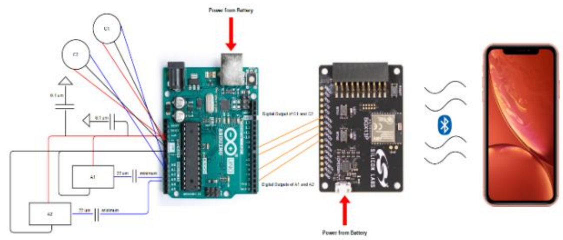

Figure 5: Wire configuration for sensors connected to the ADC which is connected to the Bluetooth Module for connectivity to the user's phone.

IV. RESULTS

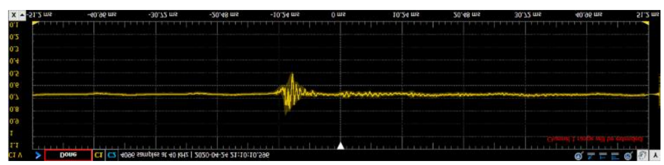

Figure 6: Proof of functionality for Airborne MEMS Sensors

V. CONCLUSION

A smart knee brace was designed to continuously monitor the progression of knee joint health. The knee brace design consists of a compression sleeve with design modifications to protect the electrical components from potential environmental or situational hazards and secure the components to ensure the user's safety while the brace is in use. The device includes contact and airborne sensors that measure the acoustics produced by the knee joint that can be analyzed to determine knee joint health. An ADC and Bluetooth Module are also implemented in the design to allow the user to access their data from their phone or computer through Bluetooth technology.

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