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ARC Knee Brace: Neoprene Knee Brace with Active Control Using Wearable Sensors †

Bilge Koyuncu *, Cevza Candan and Banu Nergis

Faculty of Textile Technologies and Design, Istanbul Technical University (ITU), Istanbul, Turkey; candance@itu.edu.tr (C.C.); uygunf@itu.edu.tr (B.N.)
* Correspondence: koyuncubil@itu.edu
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Abstract: Remote monitoring of a patient's physical rehabilitation process after knee surgery is crucial, especially in instances like pandemics, where patients may not be able to get ongoing postoperative care owing to the precautions implemented. Wearable technology can be used to track a patient's development and ensure that they follow rehabilitation guidelines. ARC (Active Rotation Control) knee brace was developed to guide and facilitate physical therapy movements of patients with knee injuries in an actively controlled manner. The system is able to trigger a visual feedback mechanism when the subject performs various knee postures. Through the Internet, caregivers could obtain patients' overall knee related rehabilitation metrics. ARC Knee Brace employs inertial motion tracking technology which is based on low-cost inertial sensors and data processing algorithms to capture user's knee posture in real-time during rehabilitation process. The inertial measurement units (IMUs) containing a combination of accelerometer and gyroscope are used as motion sensors to measure accelerations and rotational rates of knee. The sensors track data including acceleration, rotation and temperature. The processing system handles calculating various metrics from the posture of knee.

Keywords: Active Rotation Control; knee brace; IMU; sensor; data processing; physiotherapy; health care; wearable technology

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1. Introduction

Knee injuries are frequent irrespective of the gender, age and demographic factors and they necessitate costly and lengthy treatment methods [1–3]. A patient's recovery from a knee injury is generally reliant on their commitment to their allocated rehabilitation procedures. It is advantageous for sportsmen to do the motions prescribed at physical therapy facilities for knee injuries while under the supervision of a professional. However, if the athlete is unable to or does not choose to visit the physical therapy clinic, these motions are performed alone. When the intended knee stretching/opening cannot be accomplished as predicted during individual studies due to the fear of making a mistake or injuring oneself, the treatment procedure and thus the time to achieve knee mobility before the damage rises.

Wearable technologies are commonly utilized in the therapeutic field to examine mechanical analyses of movement in neurological and orthopedic disorders. In this approach, they contribute to the development of the patient's treatment programs. There are many researches on joint angles and moments in the literature. As estimates, they attempt to represent muscle strengths and patterns [4]. Biomechanical data may also be provided in real time to patients, by using wearable technology, to enhance their effectiveness in therapeutic workouts than by a physical therapist's verbal or tactile input [5–7].

CPM or isotonic movement devices on the market are typically utilized as passive motion moving devices to ensure joint mobility in the injury rehabilitation process without an active muscle contraction. Although medical experts' overall assessment of the benefits of these devices is positive; such devices do not allow the muscle to contract voluntarily, and thus, depending on the patient's condition, the expected effect in regaining "old" muscle strength may not be seen. Products such as patella open lateral support knee pads, which are prescribed for athletes with knee injuries, are typically meant to assist the athlete protect himself and/or promote such motions during everyday routine activities (such as walking). And some of such products have been employed together with CPM or isotonic movement devices [8,9]

To propose a solution to the aforementioned technical problem, an electronic circuit was developed, which can be integrated in to a medical textile product (e.g., knee pads, knee cuffs) and a code (software) for this circuit was written to produce data about whether the individual performs the expected opening in the knee by measuring the angle (in the context of opening in the knee), duration, state of motion, and acceleration of motion while she/he performs the physical therapy movements prescribed.

2. Material and Method

2.1. Material

A patella open lateral support knee pad is used as a substrate to integrate the electrical designs such that it largely results in dependable and minimum patient obstruction. That is to have a suspension and plug system which includes electronically controlled sensors, serial module for *Arduino* Wi-Fi ESP8266, light diode that are practical, safe and easy to use. Electronic components and software work for data that can both capture graphs of all data and mirror them. Wi-Fi serial transceiver module and sensors are covered using special cases created with the help of three-dimensional printing techniques. This means that the durable equipment may be changed not only because of the protection type but also gadget parts. Easy operation relates mainly to a basic mechanism and little modification in personal use. The surface also features some rectangular sections that are suspended for electronic design. Control of the ARC knee brace does not have a location sensor which is very expensive and not easy-to- find. GPS data, on the other hand, is not appropriate for axial rotation movement. Gyro sensors are designed to monitor the angular rotation rate. Small sensor units with a data logger and sensor head are utilized for the sensor system. It is based on the system of 'x,y,z' [10]. For the reasons outlined, the design includes MPU6050 Gyro sensors. However, the gyro sensor contains too much data and therefore an additional (complimentary) filter is often required that is also has a downside. In an attempt to avoid this problem, the first sensor is attached to the ESP8266 and the voltage source is connected (Figure 1a). Finally, the i^2c gyro sensor MPU6050, on the other hand, offers data transfer through 0x68 channel given in Arduino Software [11] (Figure 1b). The relevant information comprises acceleration, rotation and temperature. The data collected for both gravitational and other accelerations are processed such that the graph of knee position against acceleration is obtained using the accelerometer's functioning principles.

(**a**) (**b**)

Figure 1. Electronic devices (**a**) IoT Wifi ESP8266 (**b**) Gyro sensors MPU6050 (0x68–0x69).

Examples of Complementary Filters (CF) include roll angle estimation, which is connected to high frequency (integrating roll rate—p) gyro output. Roll angle is related with turning rate. Using the complimentary filtering process enabled the monitoring of the knee's motion position as a result of avoiding noise, which provided much clearer data reading.

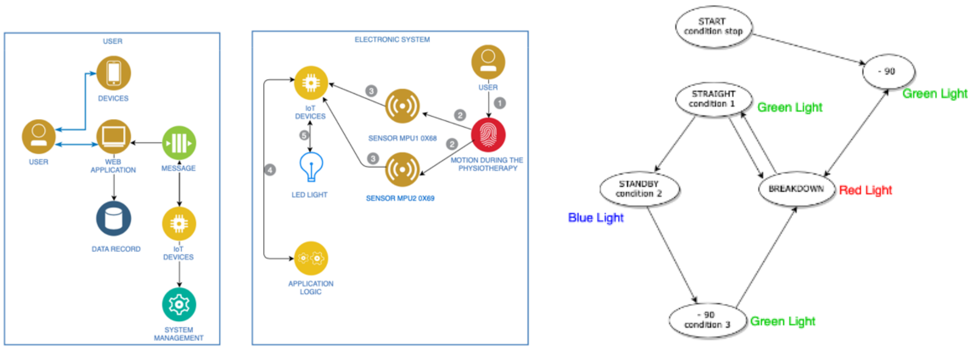
2.2. Method

Modelling and Prototype Development

Arduino Wi-Fi module ESP8266—which assists to create the knee-brace so as to operate different gadgets- is utilized for our modelling. It is operated through Wi-Fi remotely and via phone applications. Arduino's input/output pins are digital. These devices are connected through a communication module with local Wi-Fi. A microcontroller is required to process data and link several modules for control in the system. Because Wi-Fi networks are widely available in public locations such as homes, the proposed wireless network may be readily operated using a Wi-Fi network. The other component of the model is LED indication. A piyotel electrical component is used as a wearable strain sensor with an LED indication [12]. The system is often referred to as a visual-control system. Strain sensors can be regarded key parts in smart sensing, such as smart visual control systems, entertainment systems, and human health monitoring, to name a few examples [12]. For biomedical purposes, a converter may be employed. They are inductors and conseders that are soft and very stretchy. These circuit components respond to tensile stretch in the planer x and y directions and compression in the transverse direction [14]. This way of producing a change in voltage facilitates the incorporation of textiles into wearable electronics systems that are utilized because they match the elastic compliance of human skin and other natural biogicial tissue, and also they may play a key role in the further versions of the circuit developed [13]. The use of condanser is therefore aimed at responding electrically to elastic deformation and may be placed on the skin and around the joints without interference from natural movement [14]. 3D priting offers great opportunities for the production and human use sectors. [15,16]. 3D printing uses the sort of filament closely associated to demand quaility. This is one of our processes in manufacturing 3D coverings for coatings of specified electronic devices and for safe storage and usage. In doing so, SketchUp 3D Design Sofware modelling programme [17] was utilized.

Extension of the knee is described as an angle increase by straightening the knee movement. Knee bending is defined as the knee bending resulting in an angle decline. The maximum values of these movements are full extension and complete flexion [18,19]. Our ARC Knee brace prototype is divided into two pieces. The first is the control patch, which houses all of the electronic components that cannot be washed. The second item is a textile based neoprene brace (patella open lateral support knee pad). Design is drawn using the AutoCAD software during computer analysis. The data library on Arduino provides the basis for this development. Arduino also includes an open source library which can be employed for acceleration, rotation, and temperature data reading for the MPU6050 gyro sensor. The angle information included in the code is expressed in term of rotation per minute (rpm), whereas the system architecture converts this very angle information to degrees. The gyro sensors (MPU6050 0x68) used for the work collect data in order to transmit IoT devices with 8 pins. VCC, GND, SCL, and SDA pins from both sensors are used in our electrical design. The second gyro sensor (MPU6050 0x69) communicates through one extra pin, namely AD0. Sensors are attached to four pins, three for LED light and resistance and one for ground. The voltage value used for active motion control smart knee brace design is 3 V, however modules can utilize 5 V. For power generation, the trial duration was set to 5 V. For LED lighting of three colors, depending on software results, a connection must be made between three distinct legs and three identically similar resistances. The goal of including a capacitor in the design is to protect IoT devices while also extending sensor lifespan. One leg is connected to the 5 V generated power for the LED light, while the other is connected to the 3 V generated power in order to power the system. The pin and color codes are established in the code. LEDs come in a variety of colors, and for the work three primary colors were chosen, such that depending on the voltage levels transmitted to the LEDs the system activates the correct color.

Figure 2a,b depict the electronic system as well as its interaction with the user. Figure 2c, on the other hand presents the working principle of the prototype, namely the algorithm of the code written. Final version of the circuit diagram of the prototype is given in Figure 3.



(**a**) (**b**) (**c**)

Figure 2. Working principles: (**a**) interaction of the system with the user, (**b**) electronic system (**c**) The working principle of the prototype.

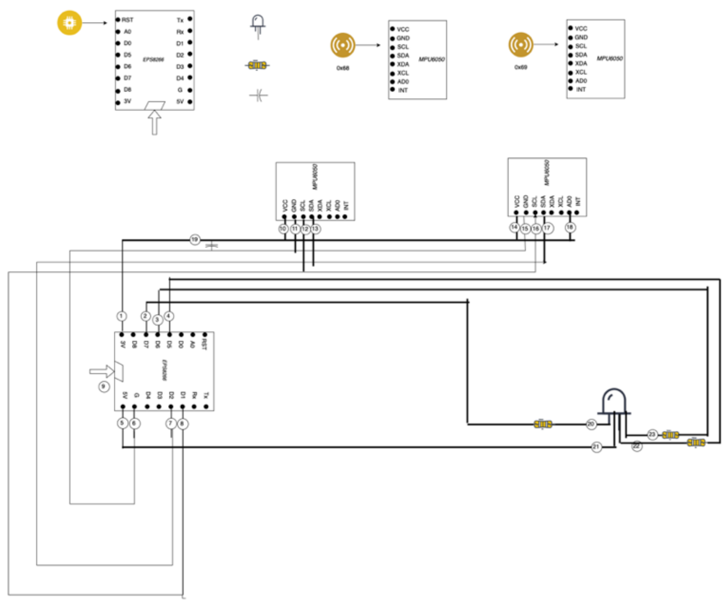


Figure 3. Circuit diagram of the ARC Knee Brace.

3. Result and Discussion

The validation of the system is given with the help of Figures 4 and 5. The prototype operates properly when it is run and it reads the angular data for the current knee position. Moreover, the system produces primary colors (i.e., red, green, blue) to warn user depending on the knee bending angle with the help of LED connected to the system (Figures 2c and 4). When the movement hits −90, the light goes green, but as it progresses through the degrees, it turns red. It also changes back to green at the angle of 0 degrees. The system waits for 20 s before it changes the green light to the blue one at the appropriate bending angle of the knee during a treatment. This blue light indicates that the movement required for that particular phase of a treatment has been completed properly. As a final note, it was demonstrated that the knee improvement can be measured by the amount of opening (in the angular sense) (Figure 4), which is a more objective criterion in comparison to the use of pain scales such as VAS (Visual Analogue Scale) testing [20].

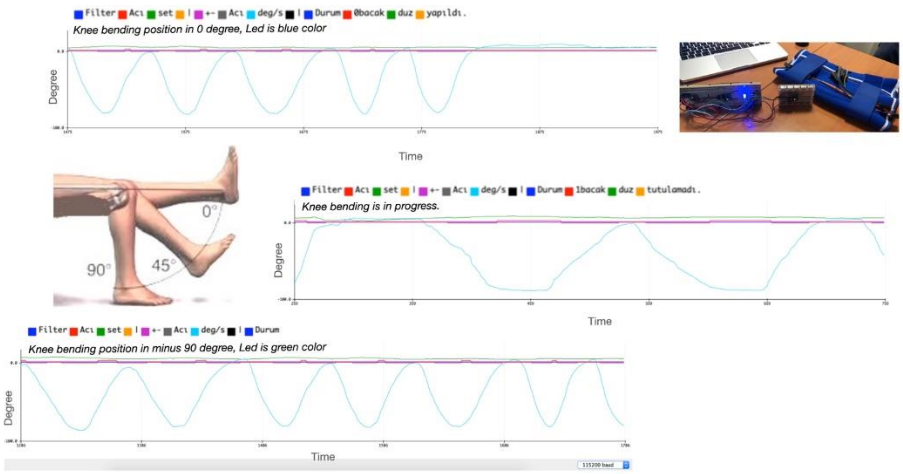
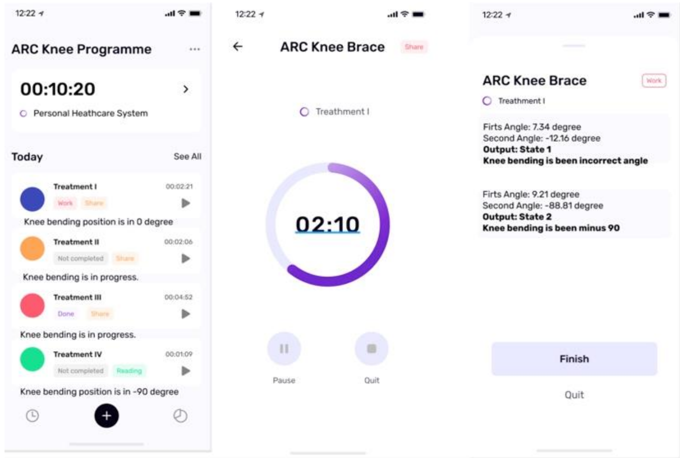


Figure 4. The prototype of the ARC Knee Brace and the momentary data taken from it for different knee bending positions from minus 90 and 0 degree (from down to up).



(**a**) (**b**) (**c**)

Figure 5. UX/UI design from the application interface for ARC Knee Brace: (**a**) exercise data collection; (**b**) timer motivation; (**c**) ARC knee brace programme outcome.

Furthermore, the UX/UI design from the application interface for ARC Knee Brace also allows the patient to capture and monitor the observed data (Figure 5).

4. Conclusions

The ARC knee brace discussed in this study contributes to physical therapy processes of athletes and/or ordinary individuals who have knee injuries. The ARC knee brace is designed for "active knee motion control", unlike to commercial systems with "continuous passive motion control". Patients can carry out the physical motions in a way he/she controls (voluntary muscle movement). Moreover, the application (software) developed for the brace can be downloaded on Patient and physician's IoT device, so that the progress of the patient may be observed objectively and recorded by the relevant professional(s). Finally, the ARC knee brace is an integrated element of a medical textile product (knee pad) and no additional space is needed for its use. ARC knee brace can also be used as a conventional knee pad at the end of a treatment process by detaching the circuit.

5. Utility Model

"Smart Knee Brace for active motion control", TPE 2020/12076, Document Registration Number: 2020-GE-333942.

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