engineering proceedings

Proceeding Paper

An IoT-Enabled Knee-Sleeve for Home Rehabilitation: A Pilot Study †

David Gibbons [1], Luz A. Magre [1,2,*] and Shirley Coyle [1,3,*]

1 School of Electronic Engineering, Dublin City University, Glasnevin, D09 Y074 Dublin, Ireland; david.gibbons8@mail.dcu.ie
2 SFI CRT in Digitally Enhanced Reality (D-Real), Dublin City University, Glasnevin, D09 Y074 Dublin, Ireland
3 Insight SFI Centre for Data Analysis, Dublin City University, Glasnevin, D09 Y074 Dublin, Ireland
* Correspondence: luz.magre2@mail.dcu.ie (L.A.M.); shirley.coyle@dcu.ie (S.C.)
† Presented at the 5th International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles, Ghent, Belgium, 14–16 November 2023.

Abstract: In this project, a smart knee sleeve was developed for the purpose of measuring a subject's knee angle continually. The device is wireless and washable, making it suitable for rehabilitation at home. Two separate methods were incorporated onto a standard knee sleeve: a flexible silicone-based bend sensor and two IMUs. Each approach was evaluated, and testing was conducted on three subjects wearing the knee sleeve, using a reference video motion-tracking method. Squats were used as the exercise protocol for testing. The results showed that the flex sensor performed better for two of the three participants, with an average RMSE of 8.3 degrees, which is comparable to results from related research.

Keywords: flex sensors; inertial measurement units; knee angle measurement; wearable technology

Citation: Gibbons, D.; Magre, L.A.; Coyle, S. An IoT-Enabled Knee-Sleeve for Home Rehabilitation: A Pilot Study. *Eng. Proc.* **2023**, *52*, 2. https://doi.org/10.3390/engproc2023052002

Academic Editors: Paula Veske-Lepp, Frederick Bossuyt, Steve Beeby, Kai Yang and Russel Torah

Published: 11 January 2024

1. Introduction

After a person undergoes knee surgery, such as an anterior cruciate ligament (ACL) reconstruction, the monitoring of the range of motion (ROM) of the knee is important for a successful recovery. During the early phases of rehabilitation, monitoring can help a healthcare professional (HCP) to track progress and better identify individual therapeutic needs for patients [1].

In a clinical setting, knee joint angles are most often measured using a goniometer. A goniometer measures the angle of the knee and the ROM is determined by finding the maximum and minimum knee angle for the patient. Video-based systems are used in some larger clinical settings and can provide results dynamically. They measure the angle of the knee using high-speed cameras with marker-based motion capture systems [2]. However, high-speed cameras are not suitable for home rehabilitation as they are expensive, and movement is limited to a small area. Due to these limitations, other methods are needed for use outside of the clinical setting, which creates a need for a wearable device to accurately measure the knee angle. This paper proposes and compares two sensing methods to obtain the knee joint angle in the sagittal plane as alternatives to current camera-based systems.

2. Related Work

Inertial measurement unit (IMU) sensors, electrogoniometers, resistive, and capacitive sensors are among the devices used for measuring knee angles. In the works of Faisal et al., Favre et al., and Li et al. [3–5], IMUs were used to measure knee angles in activities such as walking, running, and walking up stairs. A current limitation of IMUs is that measurement drift can be an issue over a longer period of time [6].

Another approach presented by Buttner et al. [1] used a potentiometer to measure the knee angle. However, this technique can limit the patient's natural movement due to its rigid structure. Resistance sensors such as those used by Watson et al. and Di Tocco et al. [7,8] can be a good option as a wearable sensor. Nonetheless, they can suffer from hysteresis issues that affect the continuity of the measurements. Capacitance sensors offer the same wearability properties, without the aforementioned issue, as seen in the work by Hermann et al., Atalay et al., and Poomsalood et al. [9–11].

3. System Design

Two measurement approaches are proposed in this work to measure the knee angle: a flex sensor (Method 1) and IMUs (Method 2). A capacitive-type flex sensor was used to measure displacement directly as the knee angle changes. In addition, IMU sensors were chosen given their accuracy and small size, making it possible to use them within a wearable device. The locations of both types of sensors are shown in Figure 1a.

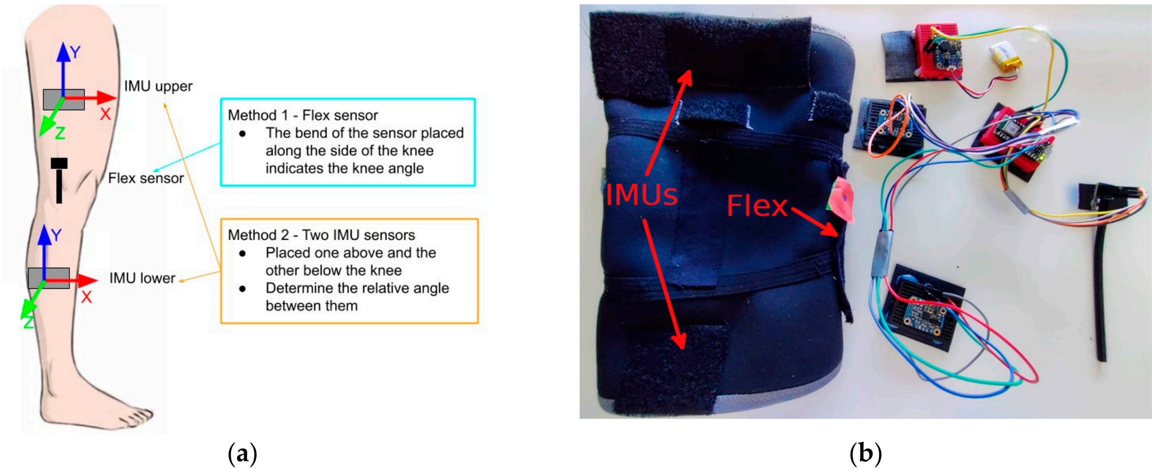

Figure 1. (**a**) Location of the sensors on the participants. (**b**) Knee sleeve and electronics detached. The overall prototype device has a total weight of 200 g.

3.1. Hardware

For Method 1, the flex sensor used was a commercial product from Nitto Bend Technologies [12]. This sensor operates by measuring the change in capacitance proportional to the curvature of the bent sensor.

For Method 2, the Bosch BNO055 [13] was chosen as the IMU due to its internal fusion algorithms to calculate absolute orientation. Two identical sensors were used, with one for above the knee joint and the other below.

An Arduino Nano BLE was chosen as the microcontroller due to its ability to send data via Bluetooth Low Energy (BLE). The flex and IMU sensors were wired to the Arduino on the I^2C bus.

3.2. Wearable Considerations

It was noted in the work of Watson et al. [7] that keeping the sensors tight to the skin resulted in better measurements, so a number of close-fitting fabrics or commercial knee sleeves were considered. The Vulkan Classic Knee support [14] was obtained as it was manufactured from close-fitting material that was durable and washable.

The flex sensor was aligned vertically along the side of the knee and held tight against the leg using a fabric pocket sewn to the knee sleeve. The IMUs were positioned in line with each other on the front part of the sleeve to rotate around one axis in the sagittal plane using hook-and-loop tape.

The final knee sleeve and electronics are shown in Figure 1b. The electronics have been separated for visual purposes, but can be reattached to the sleeve for use.

3.3. Software

Regular sampling of the sensor registries was performed with a sampling rate of 25 Hz. This is quite low compared to other studies and could have been increased to 100 Hz. However, 25 Hz was sufficient to capture the movement of lower extremities [15] for the chosen exercise regime involving slow repetitions.

In order to provide user feedback and record the values, a desktop application was developed. The application provided near-real-time visual feedback of the knee angle through a graphical user interface, shown in Figure 2, which displayed the current knee angle reported by the IMUs (green) and Flex sensor (red).

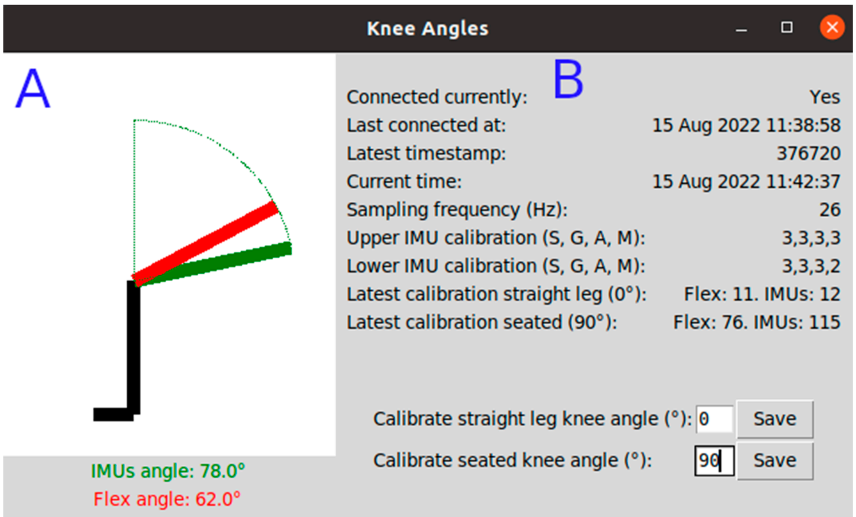

Figure 2. Desktop application interface with angle display (**A**) and collection/calibration details (**B**).

4. Testing and Results

Subject Testing

After an initial stage of testing on a custom rig which allowed for setting the knee sleeve at a known angle (see Video S1), the next stage of testing involved subjects wearing the device (See Video S2). Calibrations were performed before each test on the IMUs, but were not needed on the flex sensor as it was factory calibrated. Tests were performed on three subjects with no history of knee issues. Squats were chosen as the test exercise due to the large knee angle range of motion. Although testing was performed on squats, it is anticipated that the device will work for other rehabilitation exercises such as hamstring curls and cycling.

To determine how effectively the wearable device reports the knee angle, a video-based tracking system was used to record exercises. All video was recorded using a Canon EOS 1000D digital camera captured at 25 frames/se. Three reflective markers were worn by each subject: on the hip; the knee joint; and on the ankle. The video clip was loaded into a 2D motion capture system called Kinovea [16]. Subjects were asked to perform ten squats at a comfortable pace.

The results from one of the tests are shown in Figure 3, which plots the flex and IMU values with the reference (Kinovea obtained) value over time.

Accuracy across the different methods was determined by taking the difference of the sensor reported angles and the reference reported angle (Kinovea) to calculate the root mean squared error (RMSE). An ideal sensor would have an error value of 0°, meaning perfect agreement with the reference value. In total, the device was tested six times, across three different subjects, with the results shown in Table 1 and the RMSE calculated.

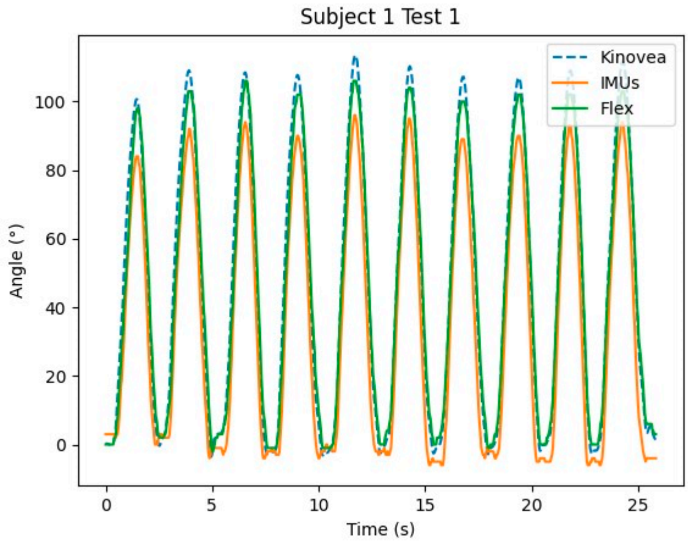

Figure 3. Flex, IMU, and Kinovea (reference) values plotted for Subject 1 Test 1.

Table 1. Results of subject testing.

Test #	Subject	RMSE (°) Flex Sensor	RMSE (°) IMUs
1	1	5.2	13.7
2	1	7.1	9.0
3	1	12.5	10.6
4	2	8.5	18.1 [1]
5	3	18.6	9.4
6	3	22.6	11.8

[1] IMUs were not fully calibrated during this test.

5. Analysis

Both sensors showed good reaction time to changes in angle as there was very little lag compared to the reference system, as shown in Figure 3. In general, the flex worked well on Subjects 1 and 2, with an average error of 8.3°.

The flex sensor is most accurate when properly aligned straight along the side of the leg at the start of the test. In this paper, the flex sensor did not work as well for Subject 3. From analysis of the video, the suggested reason for this was that the flex was impeded at times during the squat cycle. This subject had a larger knee than the other subjects, so it is suggested that a larger knee sleeve was needed.

The IMUs worked well on Subjects 1 and 3, as seen in Table 1. The test for Subject 2 was not completed correctly due to an issue with internal calibration. The main source of error for the IMUs was underestimating the max angle of the knee by 10° or more.

Comparing the flex sensor to the IMUs, the lack of internal calibration on power up is certainly an advantage for the flex sensor. Continuous calibration is not practical for regular use, especially as a home rehabilitation device. The flex did not have this issue. The flex is also composed of a single component, as opposed to two IMU components, which is also important for a lightweight solution.

6. Conclusions

This paper implemented a washable, wireless device to allow the tracking of the knee angle during rehabilitation exercises. There is a need for such a device as the current methods are limited to a clinical setting.

The device was tested on three subjects. The flex sensor showed good results on two of the three subjects with a low average RMSE of 8.3°.

Future work has been identified to investigate ways to improve the device through further research on flex sensor alignment and IMU orientation algorithms. Each change should ensure that the device remains comfortable and convenient to wear. Future testing is also needed on a larger range of subjects, performing different rehabilitation exercises.

Supplementary Materials: The following supporting information can be downloaded at: Video S1. Testing with rig setting angles at 0°, 45°, 90°, and 135°: https://drive.google.com/file/d/12CFZWc3buth1OOUEYQw_6ym4ZG3Ad4KD/view?usp=drive_link (accessed on 18 January 2023); Video S2. Subject 1 Test 1 with Kinovea annotations of squats: https://drive.google.com/file/d/1hmN1ul-9iWp20UJW0T1nRtFUxEgGcEUb/view?usp=drive_link (accessed on 18 January 2023).

Author Contributions: Conceptualization, Methodology and Analysis, D.G., L.A.M. and S.C.; writing—original draft preparation, D.G. and L.A.M.; writing—review and editing, supervision, project administration and Funding acquisition S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Insight Research Centre for Data Analytics and the Centre for Research Training in Digitally Enhanced Reality (d-real) at Dublin City University (SFI/12/RC/2289_P2, 18/CRT/6224).

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki, and was approved by the Research Ethics Committee of Dublin City University (DCUREC/2023/054 19 April 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Results are available in this manuscript and additional data can be provided on request.

Acknowledgments: The authors acknowledge Kieran Moran for the guidance given for this work.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Buttner, C.; Milani, T.L.; Sichting, F. Integrating a potentiometer into a knee brace shows high potential for continuous knee motion monitoring. *Sensors* **2021**, *21*, 2150. [CrossRef] [PubMed]
2. Saggio, G.; Quitadamo, L.R.; Albero, L. Development and evaluation of a novel low-cost sensor-based knee flexion angle measurement system. *Knee* **2014**, *21*, 896–901. [CrossRef] [PubMed]
3. Faisal, A.I.; Majumder, S.; Scott, R.; Mondal, T.; Cowan, D.; Deen, M.J. A simple, low-cost multi-sensor-based smart wearable knee monitoring system. *IEEE Sens. J.* **2020**, *21*, 8253–8266. [CrossRef]
4. Favre, J.; Jolles, B.; Aissaoui, R.; Aminian, K. Ambulatory measurement of 3d knee joint angle. *J. Biomech.* **2008**, *41*, 1029–1035. [CrossRef] [PubMed]
5. Li, M.; Torah, R.; Nunes-Matos, H.; Wei, Y.; Beeby, S.; Tudor, J.; Yang, K. Integration and testing of a three-axis accelerometer in a woven e-textile sleeve for wearable movement monitoring. *Sensors* **2020**, *20*, 5033. [CrossRef] [PubMed]
6. Faisal, A.I.; Majumder, S.; Mondal, T.; Cowan, D.; Naseh, S.; Deen, M.J. Monitoring methods of human body joints: State-of-the-art and research challenges. *Sensors* **2019**, *19*, 2629. [CrossRef] [PubMed]
7. Watson, A.; Sun, M.; Pendyal, S.; Zhou, G. Tracknee: Knee angle measurement using stretchable conductive fabric sensors. *Smart Health* **2020**, *15*, 100092. [CrossRef]
8. Di Tocco, J.; Carnevale, A.; Presti, D.L.; Bravi, M.; Bressi, F.; Miccinilli, S.; Sterzi, S.; Longo, U.G.; Denaro, V.; Schena, E.; et al. Wearable device based on a flexible conductive textile for knee joint movements monitoring. *IEEE Sens. J.* **2021**, *21*, 26655–26664. [CrossRef]
9. Hermann, A.; Ostarhild, J.; Mirabito, Y.; Bauer, N.; Senner, V. Stretchable piezoresistive vs. capacitive silicon sensors integrated into ski base layer pants for measuring the knee flexion angle. *Sports Eng.* **2020**, *23*, 22. [CrossRef]
10. Atalay, O. Textile-based, interdigital, capacitive, soft-strain sensor for wearable applications. *Materials* **2018**, *11*, 768. [CrossRef] [PubMed]
11. Poomsalood, S.; Muthumayandi, K.; Hambly, K. Can stretch sensors measure knee range of motion in healthy adults? *Biomed. Hum. Kinet.* **2019**, *11*, 1–8. [CrossRef]
12. 2-Axis Soft Flexible Sensor-Bend Labs. Available online: https://www.nitto.com/eu/en/nbt/products/2-axis-soft-flex-sensor/ (accessed on 2 April 2023).
13. Bosch Sensortec. Intelligent 9-Axis Absolute Orientation Sensor. Available online: https://www.bosch-sensortec.com/products/smart-sensor-systems/bno055/ (accessed on 18 January 2023).

14. Classic Knee Support (3029). Available online: https://vulkansupports.com/product/classic-knee-support-3029/ (accessed on 2 April 2023).
15. Bloomfield, R.A.; Fennema, M.C.; McIsaac, K.A.; Teeter, M.G. Proposal and Validation of a Knee Measurement System for Patients with Osteoarthritis. *IEEE Trans. Biomed. Eng.* **2019**, *66*, 319–326. [CrossRef] [PubMed]
16. Kinovea. Available online: https://www.kinovea.org/ (accessed on 17 January 2023).