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Comparison of Wearable and Computer Vision Based Approaches to Knee Flexion Angle Measurement

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Abstract: This paper outlines the development of a wearable device to measure knee joint flexion angles and compares its performance to a computer vision based human pose model. The objective is to advance techniques used in measuring joint flexion angles, which have several drawbacks such as relying heavily on the clinician for accuracy while also being invasive as they require physical contact between the patient and orthopaedic specialist. The proposed implementations integrate digital innovation in orthopaedic healthcare while being affordable and easy to deploy, making them marketable to clinicians and patients in developing countries. To evaluate the workability of the implementations, knee flexion angle measurements of a test subject were obtained using both techniques which yielded consistent and comparable flexion angle readings. Further development of this work can have a significant impact on the accessibility and affordability of innovative healthcare monitoring technologies, especially for patients in developing countries.

Keywords: Joint Flexion Angle, Orthopaedic Care, Human Pose Model, Wearable Device

1. Introduction

The joints of the human body play a crucial role in enabling smooth and precise movements, thereby facilitating numerous activities performed by human beings. For instance, the knee is an important load-bearing joint of the human frame that plays a major role in supporting the upper body when standing or in motion [1]. The forces acting on this joint range between 2 to 3 times the body weight, exposing the joint to a variety of load conditions that make it one of the most vulnerable to injury or trauma. This degenerative wear on the joints, which can sometimes be post-traumatic, leads to a condition known as osteoarthritis. It occurs when flexible tissue at the ends of bones near the joints wears down. Obesity, lifestyle diseases, and ageing are also among some of the causes of wear and tear on the joints [2,3]. This is not only a problem in modern cities but also in rural Kenya where specialist treatment is limited. In Kenya, the number of orthopaedic surgeons is estimated at around 100 but those registered and accredited by the Medical Practitioners and Dentists Board are less than half that number, with most of them practising in urban cities and hospitals. This means that the ratio of the Kenyan population to the number of orthopaedic surgeons (1.1 million to one) is way below the WHO-accepted figure of 100,000 to one [4]. Treatment for degenerative wear on the joints varies depending on the cause, the severity of the pain at the knee joint, and any subsequently arising joint

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deformities. If conservative methods do not diminish the pain at the joint then surgery is a common treatment method through knee replacement. Total Knee Replacement (TKR) is an effective treatment procedure for osteoarthritis patients [5]. However, after the procedure, some TKR patients suffer from postoperative knee stiffness and reduced knee flexion within their range of motion. Such patients, therefore, need appropriate management options, such as physiotherapy sessions to track their progress in trying to restore optimal flexion of the joint. Restricted postoperative knee flexion is the most frequent complication after TKR procedures and also the main cause of patient dissatisfaction due to the limited range of motion of the joint [6].

Currently, orthopaedic specialists use goniometers [7] and estimated passive observation to measure a joint's angle of flexion within its Range of Motion (ROM). Goniometers have been around for a while and have some shortcomings associated with their use among them being highly prone to human judgement and errors when measuring the flexion angle of a joint. They are also more invasive, as the specialist has to come into physical contact with the patient when using the goniometer to extract readings from it.

Other modern technologies used to conduct gait analysis and joint flexion measurements are expensive. For example, ProtoKinetics, which is based in the US, have developed a Gait Analysis Software and have patented the Zeno Walkway Gait Analysis System [8] capable of providing meaningful human pose data to clinicians and researchers, although at an expensive fee due to the cost of development of their system and integration of expensively acquired pressure and precision camera sensors. However, such solutions are hard to access especially for specialists and patients in low and middle-income countries especially here in Africa. As such, a need arises to develop digital and innovative solutions that are not only cost-friendly but are also less invasive and can accurately measure and record human joint flexion angles.

In this research, we develop two methods of approximating the human joint flexion angles and then conduct a comparative analysis of the two implementations. The ultimate goal is to deploy the overall system in a clinical setting for use by orthopaedic clinicians and patients. These methods enable the digitization of joint flexion angle measurements and allow for the tracking of a patient's recovery trajectory through analysis of the flexion angle data stored in the cloud. The implementation will also be beneficial to the patient, as they will be able to see if they are making progress in recovery by having them access the cloud data via a view-only web application that we intend to develop. The patient can also acquire the system for their personal use, as they might want to regularly check if they're making progress in recovering maximum flexion of a joint without having to make multiple visits to a clinician, who will also have remote access to the flexion angle data that the patient is recording.

After developing the system with the stated requirements and specifications, we intend to deploy it to an orthopaedic health centre and obtain flexion angle measurements from actual patients so as to test the accuracy and reliability of the system. Data security is one of the fundamental concerns in the growing digital healthcare space. It is paramount to ensure the privacy of sensitive patient's information when collecting their medical data and as such we intend to obtain necessary ethical clearances before testing on patients.

Once the proposed system has been successfully deployed with positive results, there is room for further modification and improvement of the prototype for diverse applications such as integrating advanced sensors that measure joint response to the reception of nerve signals that control the motion of a joint. This builds on the joint flexion angle measurement objective of our proposed prototype and tries to analyse the flexion of the joint to a deeper extent by considering the musculoskeletal structures attached to a specific joint i.e. muscle tissue, tendons and nerves. The implementation could also be used in prosthetics given that technical innovations are now being applied in making artificial limbs much more

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comfortable, efficient and as life-like as possible. Such applications show the significance of this project in being able to impact a variety of medical fields that are being revolutionised by technological innovations.

2. Objectives

The main goals of this paper include the following:

1. Developing the hardware and software of a wearable IoT device for measuring joint flexion angles and designing a computer vision based human pose model to simultaneously estimate the joint flexion angles from real-time video input.
2. Implementing the two methodologies to run on a small footprint i.e. Nvidia's Jetson Nano for ease of deployment to remote areas benefiting clinicians who will have a digitised way to measure and track the recovery of patients. We also aim to develop the prototype such that it can also be used by a patient to track their recovery at the comfort of their home without having to make frequent visits to the specialist.
3. Drawing comparisons between the joint flexion angles approximated by the wearable device and the human pose model that will enable us to have accurate measurements of the joint flexion angle.

3. Methodology

3.1 The Knee Wearable Device Implementation

In this implementation the intention is to have the patient put on the wearable device [9], flex the recovering knee joint under consideration, and as they do so the measured angle is recorded in a real-time database, InfluxDB, from which we read and display the angles in a gauge plot. Figure 1 below shows the overall system architecture of the knee wearable device.

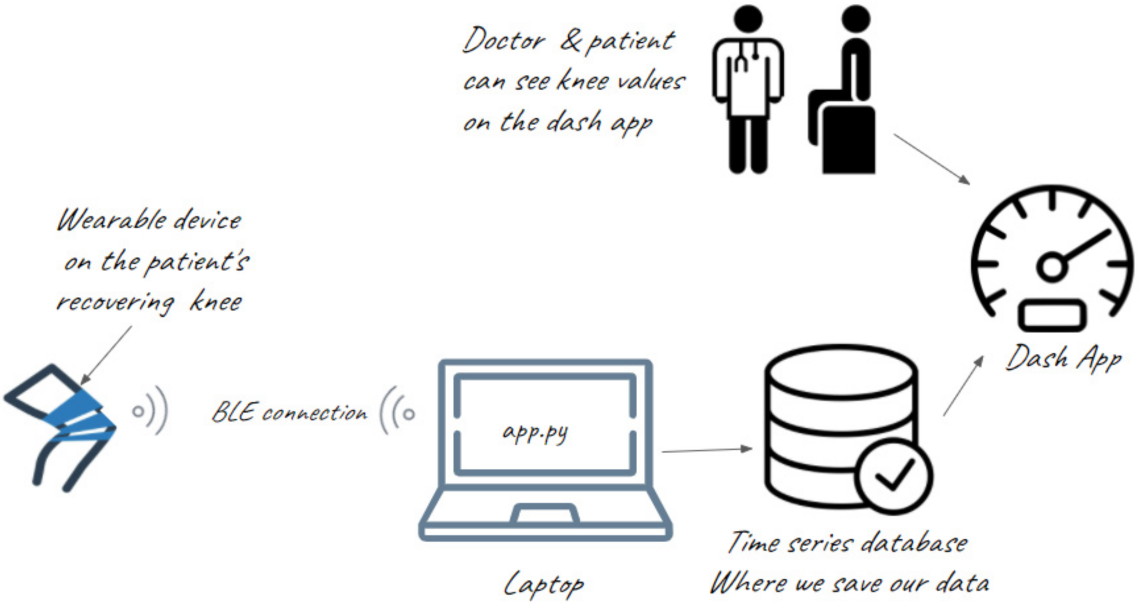

Figure 1. System Architecture of the Knee Wearable Device.

3.1.1 Hardware Description

The wearable device is made up of a knee brace and five main hardware components. They include: Arduino Nano 33 BLE Sense [10], 4.5" flex sensor [11], 3.7v Lithium-ion battery, a switch and 10kΩ resistor. There are several factors we need to consider in selecting the most appropriate sensor for accurate flexion angle measurement. In this implementation we

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use the flex sensor to get flexion angle measurements. The flex sensor is attached to the knee brace to measure the changes in the flexion angle of the knee joint. Alternative implementations could use an Inertial Measurement Unit sensor, which integrates a gyroscope, accelerometer, and magnetometer for more accurate flexion angle measurements. The flexion angle data is processed by Arduino Nano 33 BLE Sense and transmitted using Bluetooth Low Energy (BLE) to the Jetson Nano for processing and visualisation. The hardware is knitted on the knee brace as shown in figure 2 below so that a recovering patient can wear the device and as they flex the knee, they are able to see the flexion angles on a real-time plot.

Figure 2. The wearable device implementation (flex sensor, battery, Arduino Nano BLE, Knee brace)

3.2 The Human Pose Model Implementation

This implementation consists of a machine learning framework for human pose estimation running on a capable microcontroller. The NVIDIA Jetson Nano [12] is the main microcontroller that runs the human pose model and also interfaces with a webcam to get real-time video input for processing. With a human subject in the field of view of the webcam, the model is able to superimpose a skeleton over the identified human frame based on various landmarks of identifiable human features. The model then identifies the targeted knee joint whose flexion angle we want to determine and consequently determines the knee joint's angle based on the position of the hip and the ankle relative to the x and y axes of the frame. Figure 3 shows the overall architecture in measuring the flexion angle.

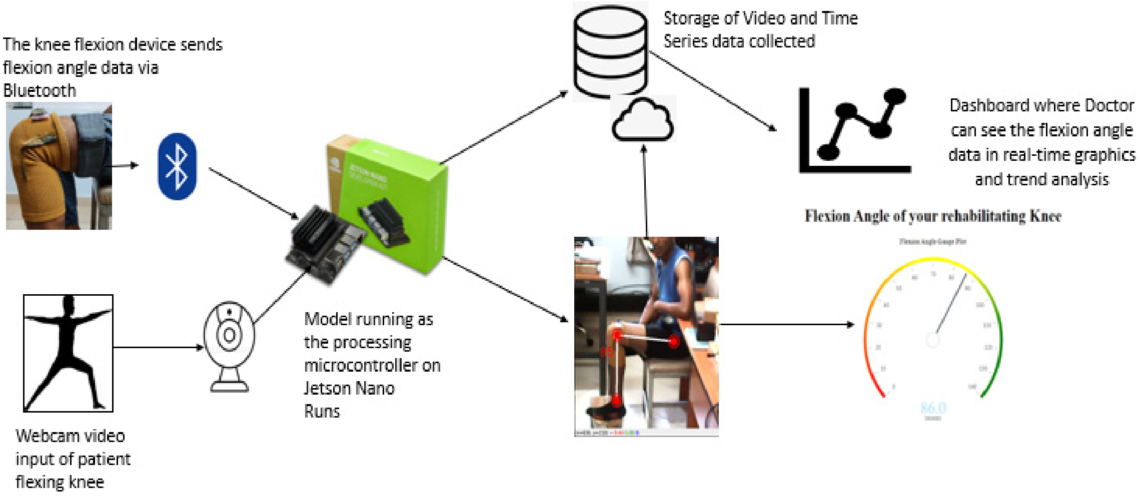

Figure 3. System architecture of the wearable device and the human pose model

3.2.1 Hardware Description

The hardware consists of a webcam and the Nvidia Jetson Nano. The webcam is connected to the Jetson Nano to record a live video stream of the patient under observation hence providing the input data for our model. The Jetson Nano is a small but powerful computer

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that runs the human pose model, which determines the knee flexion angle. It runs the algorithm's pipeline and gives an output video stream with the measured flexion angle that is simultaneously stored in the InfluxDB database.

The Jetson Nano is a preferable choice for this experiment as it is an affordable and accessible microcontroller that is capable of carrying out machine learning tasks while also being capable of running deep learning and AI applications. This is made possible by the fact that it integrates GPU cores (128 CUDA cores) in its processing architecture. GPU cores are better in terms of running multi-dimensional parallel processing which is crucial for machine learning applications and batch processing of real-time image data.

3.2.2. Software Description

The software implementation of the human pose model utilises a two-step detector-tracker machine learning pipeline which has proven to be effective in accurately tracking the human pose. This human pose model is based on MediaPipe[13], a cross-platform and open-source machine learning framework to perform computer vision perception pipelines over live video streams, images, or stream media. The model first locates the person's region of interest (ROI) within the input image frame. Then the human pose detector part of the pipeline predicts the location of 33 pose landmarks of the human frame, as shown in figure 4, and the segmentation mask within the detected ROI. The model was trained on a COCO dataset [14], a large-scale object detection dataset that is optimised for detecting human beings and localization of a person's key features in real-time.

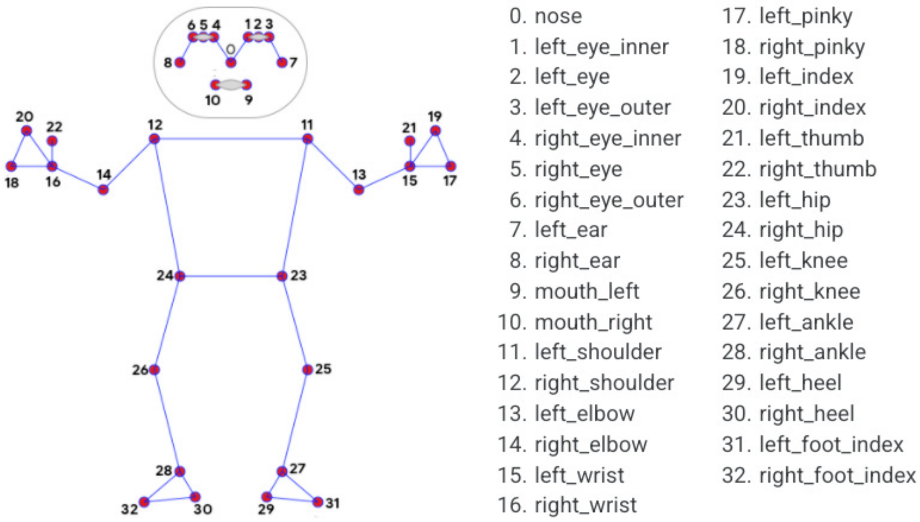

Figure 4. Human Pose Landmarks (Source Mediapipe)

To determine the knee flexion angle, the model focuses on the landmarks allocated for both the right and left knee independently, as shown in Table 1. The landmarks remain constant regardless of the direction an individual is facing on the input frame.

Joint	*Pose Landmark Joints to Consider*
Right Knee Joint	*24, 26, 28*
Left Knee Joint	*23, 25, 27*

Table 1. Landmarks that are considered to derive the flexion angle of specific Joints

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6. Results

The two implementations were put to the test and the flexion angles obtained from the two methodologies were compared as shown in figures 5, 6 and 7. The second author of this paper wore the wearable device and at the same time positioned himself within the webcam's range of view to measure the knee flexion angle simultaneously. We focused on three main positions of knee flexion; standing, seating, and squatting. The knee flexion angles obtained by both implementations are then logged in real-time in a time series database, InfluxDB. Additionally, the implementations included local storage of flexion data in a CSV file, which was then imported to a Jupyter Notebook. The graphs shown in figure 5, 6 and 7 were generated from the Notebook to show a clear visual comparison of the data collected.

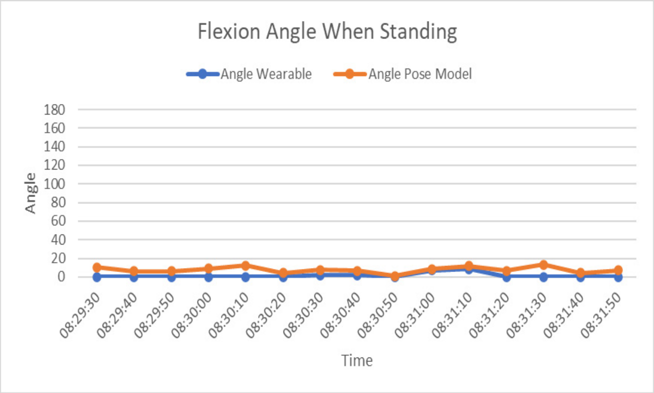

Figure 5. Flexion angle while standing

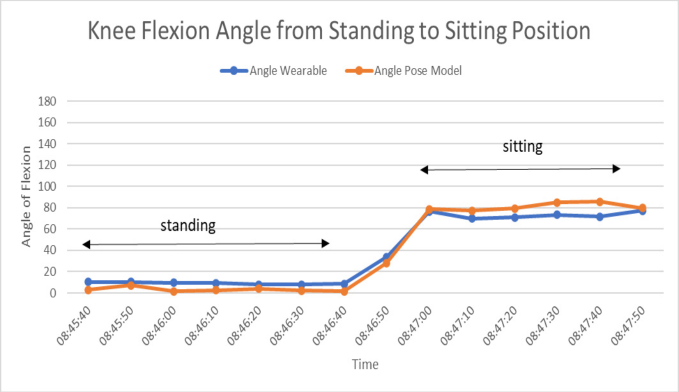

Figure 6. Flexion angle from standing to sitting position

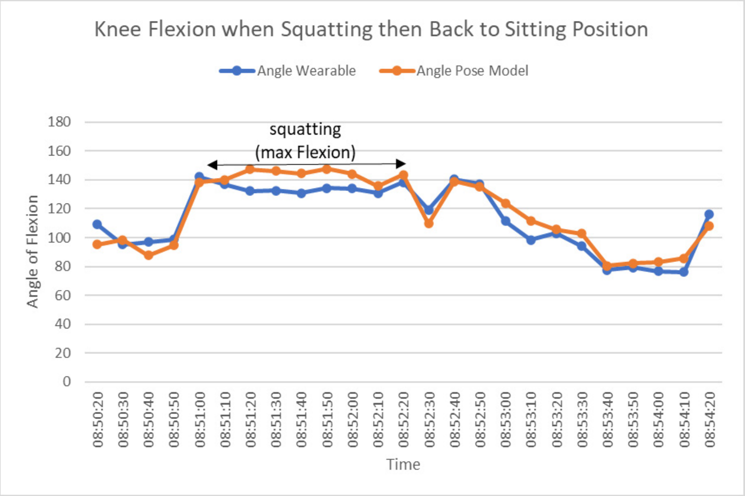

Figure 7 Flexion angle when squatting then back to sitting

7. Discussion

The results above show a direct comparison between the knee flexion angles estimated by the wearable device and the human pose model working in tandem. Figure 7 is a graph showing the comparison of the two readings when the subject is standing upright. As expected, there is near zero flexion from both readings because the flexion of the joint is zero when the leg is fully extended. Figure 6 shows the results of the transition from a standing position to a sitting position while figure 7 is showing a transition from a sitting position to squatting (maximum flexion) and then back to the sitting position. When seated the expected angle of knee flexion averages between 80° to 90° and when squatting it lies between 130° to 140°.

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These preliminary results show that the implementation of the developed prototype works for real-time joint angle measurements providing consistent values that act as a baseline of reference to each other as well as storing the data in real-time, in an online database for display and reference at a later time. Compared to current methods that manually document and track the flexion angle of patients, the proposed methods aim to automate flexion angle measurement and promote remote monitoring of flexion by either the patient themselves or by the specialist.

However, there are a couple of lessons learnt during development and deployment that result in some outlying values being measured. This presents us with the challenge of improving the current implementation so that we get accurate joint measurement values at every instance of time. Currently the wearable device uses a flex sensor that has to be positioned in a specific point at the side of the knee for consistent angle measurements. We intend to do further research and implement the wearable device using an Inertial Measurement Unit sensor that will provide even greater accuracy as a reference point for our joint angle measurements. The human pose model applied can also be fine-tuned for higher accuracy in prediction of accurate flexion angle values and we could do this by creating a dataset and training a model specifically on the orthopaedic dataset for a more specialised and more accurate model.

The results shown in this paper are from testing the prototype internally because the test subjects considered were healthy with no orthopaedic complications. As such, validation of this solution is needed on a wider scale especially by testing the prototype on recovering orthopaedic patients and this constitutes further developmental work that is needed before the prototype can be considered for production. With further advances in the implementation and improvements in technicalities of the prototype, we will be able to not only get more accurate data from recovering orthopaedic patients but also eliminate the frequent need for patients to physically visit the hospital for regular check-ups. This means that a remote rehabilitation alternative will be available extending patient-doctor interaction beyond hospital walls.

8. Business Benefits

The proposed project has the potential to be a resourceful tool for IoT and AI integration in healthcare systems especially in Kenya. Once the prototype is developed as per the stated requirements and ultimately deployed, the proposed system will be immensely beneficial to not only the orthopaedic clinician but also the patient. The clinician at the health centre will be able to digitise the measurement of joint flexion angles and that will complement the actual flexion angle values obtained using goniometers. Additionally, the clinicians will also be able to see the trend of recovery of a patient by analysing the flexion angle data that will be stored in the cloud over an extensive amount of time. The implementation will also be beneficial to the patient as they will be able to look up the trend in their flexion angle values via a view-only web application that we intend to develop. Furthermore, the patient might want to regularly check if they are making progress in recovering maximum flexion of a joint without having to make multiple visits to a health centre. Additionally, the implementation can be interfaced with mobile devices such as smartphones, which have become increasingly important in promoting health care [15,16]. The development of these techniques will make orthopaedic data collection more robust and accelerate the adoption of remote monitoring of patients. This shows the immense potential that the proposed prototype has for commercialization and integration in low and middle-income settings, where patient data is often stored in manual records and where patients may face long distances to reach hospitals.

The proposed prototype will be a low-cost device that has a small footprint and will consist of the package containing the webcam with the main microcontroller as the Jetson

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Nano and the wearable device, which is interfaced with the Jetson Nano. The components used for development are widely available locally ensuring reproducibility is not an issue if need arises to commercialise the prototype for wide scale deployment. The overall development costs for both the wearable and the human pose model is about $160 for the components and circuitry without considering the cost of labour and effort put into development and also without considering deployment costs, which include visits to an orthopaedic centre for testing on actual patients.

The journey towards getting the proposed prototype to market is mainly characterised by repeated testing of the implementation by deploying the prototype and collecting data from multiple patients in health centres over a significant period of time. The main requirement for the solution to actually be ready for the market is that we achieve acceptable accuracy in joint angle measurements from a significant number of rehabilitating orthopaedic patients using the prototype.

Taking these preliminary steps will move us towards offering a more convenient and less costly alternative to joint rehabilitation by providing innovative joint angle measurement solutions and enabling remote monitoring of patients at their homes which ultimately contribute to better patient outcomes [17].

9. Conclusions

In this research project, we developed a wearable device and a human pose model to measure the angle of knee flexion and store the data in a time-series database. The data is then visualised in real-time on a dashboard showing the trend of recovery of an orthopaedic patient. Our preliminary results show the potential of the implementation and demonstrate acceptable measurements from both implementations. We demonstrate that the collection, storage, and real-time visualisation of knee flexion angle data can be achieved and with further development of the prototype, patient-doctor interaction can be extended beyond hospitals. Additionally, this work promotes the adoption of more innovative orthopaedic monitoring techniques and initiates preliminary steps towards remote and digitised patient monitoring.

The methods described in this paper have been met with several challenges including budgetary constraints limiting the choice of suitable sensors and microcontrollers for more accurate joint measurement values. The implementation also deals with patient’s personal health data hence the need to consider ethical handling of such data. It is paramount that we ensure the security of sensitive patient’s health records as data security is one of the fundamental concerns in the growing digital healthcare space.

Further research work has to be done in development to ensure the accuracy of joint angle measurements as all medical diagnosis techniques have to be highly accurate for proper and effective treatment and recovery. The next steps in development will involve collecting additional data from recovering orthopaedic patients in a hospital setting to further validate and refine our approach. Successful deployment of the implemented prototype in the hospital setting will be a crucial step toward achieving the objective of deploying for remote use be it by the patient or the clinician.

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