Rehabilitation on the go: Measuring stationary and dynamic knee joint angles using accelerometers optimized for patient usability.

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***Abstract*—The field of movement analysis is an important tool for many medical decisions as well as its usage in rehabilitation. There has been research done into the field with varying approaches, such as cameras and other optical devices. The focus in this study is the usage of inertial measurement unit (IMUs) for measuring the knees angle. A problem with using IMUs is sensor placement. Multiple approaches have been promoted, some with the usage of multiple IMUs, some with an automatic calibration and others with an assumed distance between the IMUs. The knee can be simplified to a hinge to ease the calculations. This project incorporates a dual common mode rejection (DCMR) solution with virtual accelerometers combined with a rigid platform with a known distance between the sensors. This allowed for a consistent measurement that in combination with a low pass filter, can accurately calculate and follow the true angle in fast movements. However, significant false angle changes might occur due to the accelerators being sensitive to external forces. We believe that the solution created allows a patient and/or user to mount the construction themselves and allow a remote operator to receive live data about the knee joints angle. And proves the usefulness and potential of using accelerometers in a rehabilitative environment.**

***Index Terms*—IMU, accelerometer, goniometry, electrogoniometry, knee, angle, IEEE**

I. Introduction

Movement analysis is fundamental in a wide range of fields, such as physical and neuro-rehabilitation, sports medicine, human performance assessment and virtual training [1]. Motion sensing and analysis instruments are widely used in high performance and lab environment, while sensing systems that provide reliable measurements of human motion throughout activity in daily life are still not common. Wearable technologies that could allow physicians and therapists to remotely supervise the patients during a rehabilitation exercise are a challenge of today [2].

Movement analysis of angles between limbs can be studied through use of goniometry. Electrogoniometry, using electrical sensors, started in the early 1970s [3] with exoskeletal measurements. It is based on flexible transducers that have a constant change in resistance when bent and therefore can be used to measure the angle of the knee.

The most widely used technology today is the usage of high speed cameras and markers placed in precise positions on the subject's skin. These are very accurate and give a good result on some specific movements but are limited in the usage because of the need of a high speed camera. Another popular technology is the use of optical angle measurements. These have gotten traction because of their accuracy. The main problem with these is the need for expensive, immobile equipment. These drawbacks limits its use in a rehabilitation program as you can only gather data at the doctors office.

One of the main areas that has been investigated is how to deal with the different angles that the knees move in. Simplifications can be made to model the knee as a hinge [4]. This simplification allows for easy usage of sensors such as IMUs, which would be placed on each side of the joint to calculate the movement and angles of the knee. IMUs have gained the reputation of being at the cutting edge of wearable motion tracking [1]. The use of IMUs in medical engineering has seen a upswing in usage because of the relative cost efficient measuring capabilities [2].

IMUs are made up by accelerometers, gyroscopes and for some applications magnetometers. Often microelectromechanical systems (MEMS) gyroscopes are used due to their small size and relative low cost and are used to measure the change of angles by studying the change of trajectory of a small oscillating mass. Magnetometers works by magnetically determining direction of the magnetic north pole to help determining the heading of the IMU. However the only sensor used in this project is the MEMS accelerometers to determine the accelerations in three dimensions by measuring the changes in positions of three small masses due to gravity and other types of accelerations.

The aim of this project is to evaluate the accuracy and usability of using accelerometers to calculate the stationary and dynamic angle of a knee, modeled as a hinge, in a test environment.

II. Method

One of the largest challenges is how to accurately place the sensors to guarantee alignment and distance to the joint which is needed for some solutions [5]. With the motivation of usability by the patient and a wish to implement a resistance in the future a rigid system was implemented. This guarantees a fixed distance between the IMUs and the joint and a set orientation of all the IMUs. Since the skin is not a smooth surface this interface helps combat this problem. Additionally a potentiometer will be integrated into to joint itself to accurately measure the true value of the angle of the joint. The potentiometer is used as a reference to compare the calculated angle to verify its accuracy. However the accelerometer data are of greater interest since it can additionally provide the orientation of the limbs.

A. Assumptions and simplifications

The primary measurement that is relevant for this project is α rotation around the z-axis using the relative orientation method shown in Fig 1 proposed by V. Medved [6].

The joint can be simplified to a simple hinge joint such that the other rotations around the knees axis can be neglected. This is a simplification that has been used in other papers and results in a acceptable error margin

B. Angle calculation

There has been a lot of research into how the angle calculations should be done. With such a rigid system the use of a simpler algorithm can be used that has been tested before. Distributed common mode rejection (DCMR) is the method used in the works

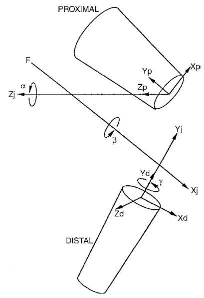

Fig. 1. Relative orientation method illustrated by Medved [6].

by Mercado et al. [5] and Dong et al.[7]. The IMUs are placed in pairs on each side of the leg as seen in figure 2 below.

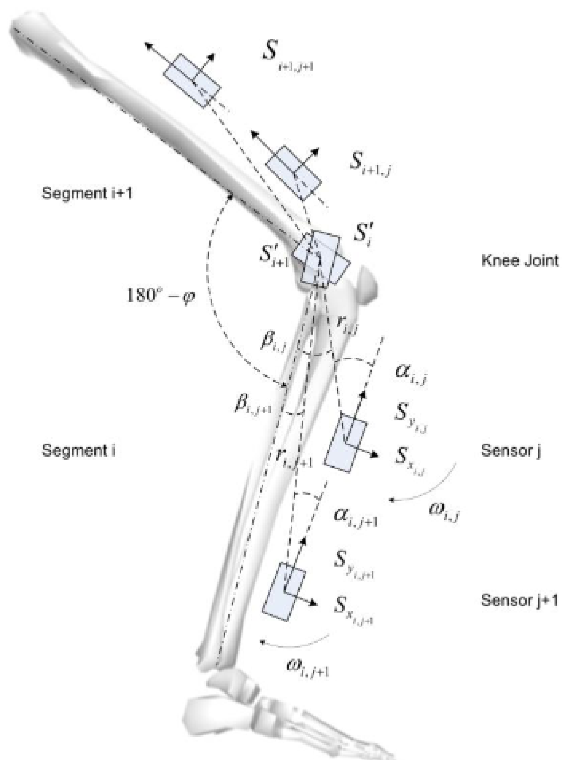

Fig. 2. Sensor placement in relation to the joint by [7]

Both the IMUs on each side of the leg are aligned with the side of the knee and has a fixed distance to the joint. This is then used to calculate two virtual accelerometers in the center of the joint. The reason to not place 2 accelerometers straight on the joint itself is the margin for error is very small [7]. The accelerometers needs to be exactly on the joint if not the angles will be full of errors as small deviations results in large errors.

The virtual accelerometers was calculated with the following equation:

$$A'_{1x} = \frac{(r_2 * A_{1x}) - (r1 * A_{2x})}{r2 - r1} \tag{1}$$

$$A'_{1y} = \frac{(r_2 * A_{1y}) - (r1 * A_{2y})}{r2 - r1} \tag{2}$$

Where A_{ij} is the real sensor i in the j direction and A'_{ij} is the virtual accelerometers. This is the straight forward calculation that is derived in [7].

$$\phi = arctan(\frac{A'_{1y}}{A'_{1x}}) - arctan(\frac{A'_{2y}}{A'_{2x}}) \tag{3}$$

C. Filtering

There has been a lot of research into what kind of filter that works best for accelerometer data, Butterworth filters with a band-pass to filter out both the static noise of the earth gravity and a and the higher noise of inaccuracies inherent in the accelerometer. The article that the placement of the sensors are based on uses a simple low pass filter with good results [7]. A Kalman filter has also been proved very successful in having a high Signal to Noise Ration(SNR).

First a band-pass filter was implemented, and it filtered the data quite well. This was before there was a reference. A problem with the band-pass filter was the filtering out of earth's gravity. This made the virtual accelerometers not having a reference. This caused problems with the calculations of the angle, which depended on having a reference force.

This made a low-pass filter the ideal choice for this project as it allows for the earths gravity to be used while also taking away the most disrupting higher frequencies.

To determine the best cut-off frequency for the filter a Fast Fourier Transform (FFT) was used to determine the necessary frequencies. For most of the tests the earth's gravity was such a dominating acceleration that the higher frequencies did not have a major impact on the calculations. This can be seen in figure 3 where the test was from a sitting position. Walking introduced more forces on the accelerometers which showed that the gravity still plays an important roll but higher frequencies were needed to fully follow the potentiometer. In some of the tests, discussed later, shows this through the FFT in fig 4

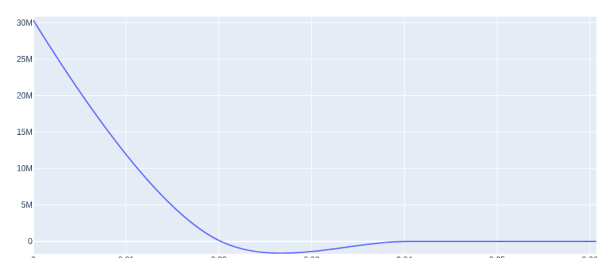

Fig. 3. FFT for sitting test.

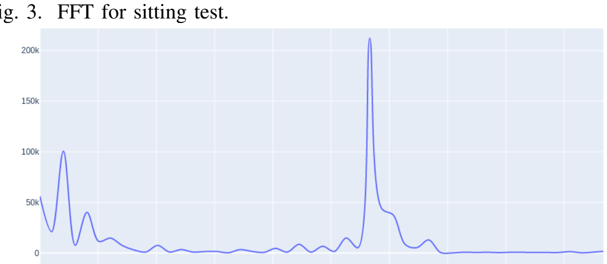

Fig. 4. FFT for walking test.

Removing the band-pass and only using a low-pass filter resulted in a well filtered signal, combined with data that can be processed into well mannered angels. Through tests the passing frequency was set to 1,5 Hz for the low pass filter.

D. Hardware

This project has used a Raspberry Pi Zero W combined with a TCA9648A I2C Multiplexer with 4 MPU6050 Inertial Measurement Units (IMUs) and a ADS1115 Analog to Digital Converter (ADC) that was connected to a potentiometer. The I2C multiplexer was required since the IMUs only had two inherent I2C addresses, but with the addition of the multiplexer the module would handle all the I2C communications between the processing unit being the Pi Zero W and the sensors.

This configuration was used together with a laser cut acrylic hinge joint with 3d-printed mountings for straps and the electronics. The total design can therefore be mounted on the side on the user's leg such that the hinge will rotate together with the knee and around the Z_j axis in Fig. 1. In figure 5 below, all hardware is assembled and mounted with straps onto a knee.

Fig. 5. Hinge design mounted to the side of a knee.

A problem that was identified in similar previous projects, such as in the work by Mercado et al. [5] is the unknown distance between different IMUs and the joint angle. This prompted the making of a hinge joint as seen in figure 5 above. The hinge was modelled in Autodesk Inventor and laser printed from acrylic. This gave a functioning prototype to test the improved solution on.

To calibrate the potentiometer, readings were taken from known angles. From the acquired data set, a linear regression model could be extracted, which was tweaked to agree with the true $\pm 90°$. The potentiometer values was kept unfiltered, and simply put into the tweaked linear regression model. With the potentiometer angle reading known, dynamic tests was also performed with the accelerometers, to allow for a direct comparison. In figure 9 below, a test where the angle where changed quickly changed was performed.

E. Software

The Zero W was chosen both for its WiFi capability, clock speed but primarily because of its distinction from a regular Micro-controller of similar size. Since it is a Micro-processor it runs a full fledged operating system, in our case the Linux based Raspian operating system. This allows for easy file management and modification, which proved to be a success for the rapid prototyping the project required. The software was coded in Python due to its ease of implementation from concept to reality together with its useful packages for visualisation of data.

F. Tests

Tests were conducted in a realistic scenario where the motions reflected the usage in a rehab setting. Tests were also conducted in other scenarios which included faster, less realistic motions. More precisely, the test where based on the following categories:

1) Stationary position
2) Sitting - sit on a table bending the knee slowly up and down.
3) Walking - 20s slow and deliberate walk, pause, another 20s walk.
4) Quick change of angle

To compare the angle calculated from the accelerometers with the potentiometer for each test, a root mean square error value was calculated as

$$RMSE = \sqrt{(\frac{\sum(\theta_a - \theta_p)^2}{N})}$$

where θ_a is the calculated angle, θ_p is the potentiometer angle.

III. Result

1) Stationary position: To test the accelerometer stationary position accuracy, the angle where set to 45°. The stationary test measurement result can be seen in figure 6 below.

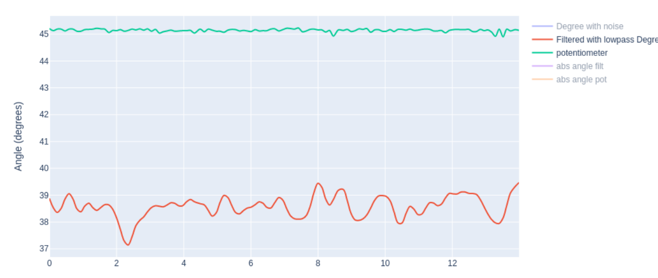

Fig. 6. Angle at stationary 45°.

The accelerometers angle RMSE is 6,58 compared against the potentiometer. It has also approximately a 5° offset from the potentiometer. This offset is consistent thorough all measurements.

2) Sitting: The sitting test measurement can be seen in figure 7 below.

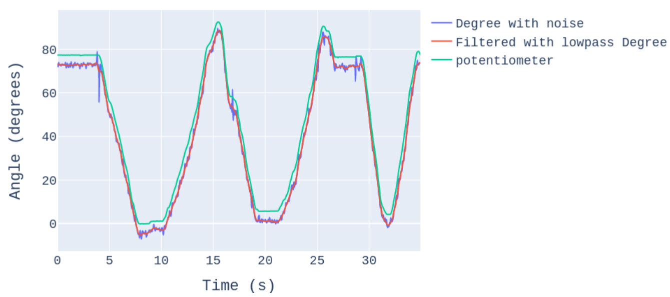

Fig. 7. Angle for sitting test.

The accelerometers angle RMSE is 5,14 compared against the potentiometer. When comparing the unfiltered angle (blue) with the filtered signal angle (red), it can be seen that the low-pass filter is reducing the signal noise quite well, removing the sharp spikes.

3) Walking: The walking test measurements can be seen in figure 8 below.

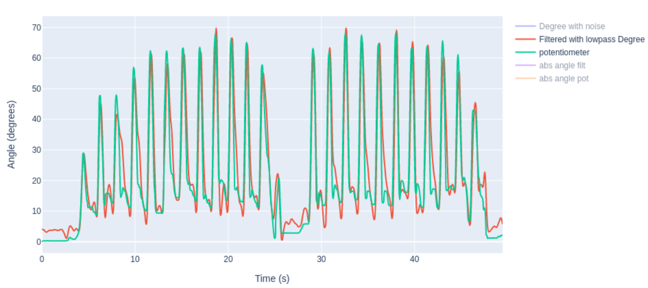

Fig. 8. Walking test angles.

The accelerometers angle RMSE is 7,07 compared against the potentiometer. Compared with the potentiometer, it registers an over/undershoot, which is further investigated in quick change of angle test. It also registers an angle change at points when the angle is in fact not moving, which can be seen after 20s, when the test person is stopping and turning around without bending the knee.

4) Quick change of angle: In testing a quick angle change, the device placed horizontally on a table with one end pointing down. The angle was quickly changed upwards. In this test, a 110° angle change is taking place in about 0.5 seconds. The angle measurements respectively the accelerations measurements can be seen in figure 9 below.

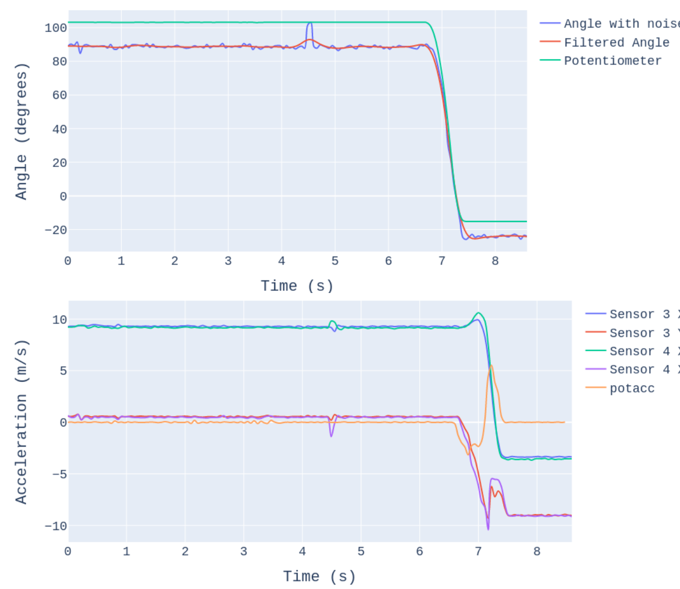

Fig. 9. Calculated angles and accelerometer accelerations.

The accelerometers angle RMSE is 13,5 compared against the potentiometer. The angle has an estimated overshoot of 2° during a time period of approximately 0.2 seconds. It can also be seen that the accelerometers registers some kind of force after 4,5 s, resulting in a false angle change of 4.8°, which is not occurring.

Another similar test, where the angle change is 100° in 0.5 seconds can be seen in figure 10 below.

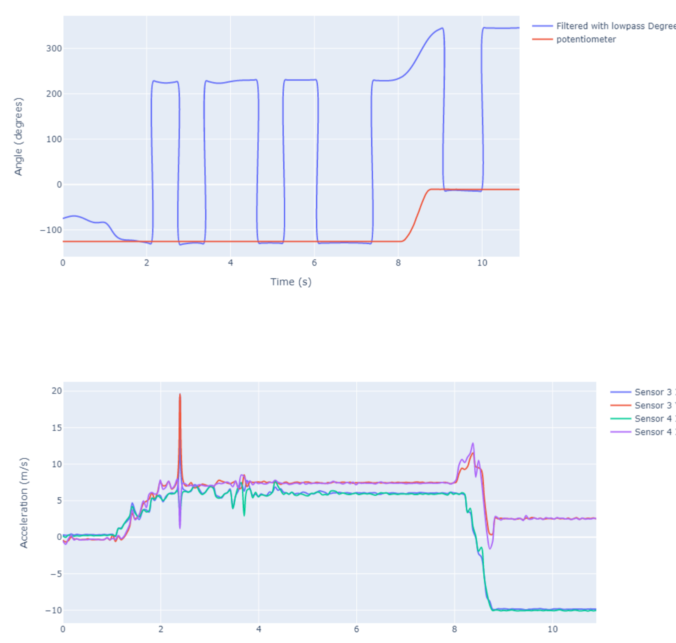

Fig. 10. Calculated angles and accelerometer accelerations.

In this test, some sudden spikes appeared in the calculated angle. The accelerometer gives 230° as the angle. Due to periodicity, a given angle on the unit circle is

$$v + n \cdot 360^\circ$$

where n is an integer. With n = -1 and accounting for the offset of 5°, it is easy to see that the spikes in fact are the same as the true angle that the potentiometer shows. Lastly, a comparison between a raw unfiltered angle with a low-pass filtered angle can be seen in figure 11 below.

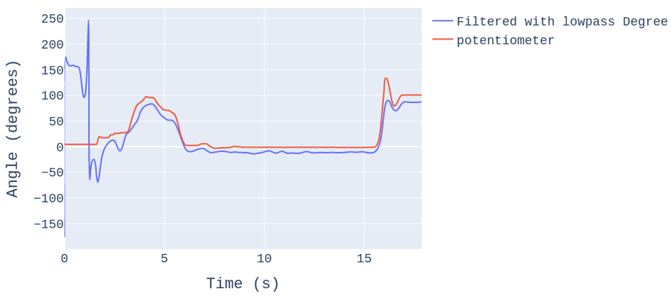

Fig. 11. Quick potentiometer and accerometer data with faulty start

This is showing how noise can give rise to huge false angles. The test results are summarized in table I below.

TABLE I

Test	RMSE	Sampling time [ms]	Frequency [Hz]
Stationary 45°	6.58	8.58	116.5
Stationary 90°	3.96	8.58	116.5
Sitting	5.14	16.6	62.5
Walking	7.07	16.6	62.5
Quick change	13.5	17.4	57.5

Also, a summary of some of the findings are listed below.

- A constant error of at least 5° is consistent between all tests.
- The sitting test had the lowest RMSE.
- In the quick angle change test, an angle overshoot of 2° during 0.2 seconds was estimated.
- Significant false angle changes might occur.
- Sometimes sudden spikes in the calculated angles.

IV. Discussion

The sudden spikes could be a result of not holding the rig completely still, since the raw accelerations are clearly changing when doing the tests. This could explain the sudden changes in the orientation. This problem can be solved in software after the angle calculation has been performed.

The chosen IMUs communicate through I2C and therefore this protocol, running at a maximum of 400 KHz, was used in between all modules. This is despite the fact that the Zero W has SPI compatibility which would allow the communication speed to reach 250 MHz, however since this functionality did not exist for the IMUs it could not be utilised. Additionally, since the signals pass through the multiplexer, the communication speed was further limited. It is believed that the time it took to record data from all sensors, the systems recording time, limited our use of the sensors in dynamic settings, however didn't really affect our stationary test. By implementing SPI communications, removing the multiplexer and implementing the recording code in a faster programming language such as C a higher recording frequency could be achieved. This would create a faster system that could increase precision and allow filters with a higher cut-off frequency and better display the motion of the knee utilising the higher resolution that would be available.

The utilisation of the accelerometer values in only the x and y directions as proposed by Mercado et al.[5] does simplify both the model and the calculations. However, this does come at a cost. If the accelerometer's z-axis is not perpendicular to the gravitational force, it will result in a disparity between the readings used to determine the angle and the true orientation of the accelerometers. This issue is more severe for the dynamic measurements since the orientation of the sensors are harder to control and the likelihood of the system retaining its perpendicular characteristics decreases further. Additionally the movements in the z direction are not recorded and disregarded for the same reason, further exacerbating the issues that derive from modelling the knee as a hinge.

Given that the knee is to be modeled by a hinge the potentiometer, after being calibrated, could provide the system with a near to true angle of the rigid construction used. Since the values for the IMU's and the potentiometer are recorded one after another there is a inherent issue that in motion the value don't represent the same position of the joint with the first IMU being furthest from the potentiometer for one given discrete step. The severity of this issue is reduced for slow movements or if a higher recording frequency could be achieved and since the individual recording-time for each value is available this difference in time can be accounted for before filtering to further reduce the impact. The high accuracy of the potentiometer and its disregard for the different movements that interfere with the accelerometers in the IMUs makes them highly reliable when only the XY-angle from the knee is sought. Using both the accelerometers and the potentiometer can allow the sensors to complement each other where the potentiometer can provide a fairly accurate XY-angle of the knee while the accelerometers can provide the orientation of the sensors to determine if the user is sitting, walking or laying down. A potential improvement for further work would be to utilise the Z-accelerometer and the three available gyroscopes in the IMUs to track the knees translations and rotations during it's movement. Here our rigid joint would limit the sensors from recording the potential rotation between the thigh and shin which the free IMUs in the work by Mercado et al. [5] would not be limited too.

With the accelerometers being able to accurately represent the angles and being very cheap the solution is working as intended. The rigid systems advantage of having fixed distance between the accelerometers and the joint allows for a more accurate calculation of the angles. To achieve the same accurate calculation with other measurement devices that is based on DCMR a fairly strict application to match the distance and orientation correctly was needed. This restriction is simplified with the rigid system, with the disadvantage of introducing a physical restriction, possibly complicating certain movements.

The accelerometer data have had quite a few bugs regarding data points and readings. As can be seen most prominently in figure 11, these readings are hard to attribute to one thing. Throughout the tests, this occurred multiple times. However it was not occurring during the "realistic" tests, indicating it might be a issue of stability in the rig when the tests was run.

The RMSE values of the realistic tests can seem quite high but when things taken into consideration such as usage, the bugs and that potentiometer being used as reference may be an acceptable value. The accelerometer data is detailed enough and is able to be used to determine the angle throughout a test. The potentiometer is a more reliable measuring device in this setting but the accelerometers has their place in more detailed motion capture.

V. Conclusion

The solution created we believe allows for rapid and relatively accurate measurement of the knees joint angle using mobile a and non-limiting construction. Given that the prototype is wireless it can transmit both live data and collected data for offsite analysis which allows for remote monitoring. This together with no lack of need for measurements or precise positioning of the sensors would allow it to be used by patients themselves without the need for onsite operators when taking measurements. We believe that the work done proves the usefulness and potential of using accelerometers to measure the mobility of a hinged joint in a rehabilitative environment.

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