Measuring Knee Compliance to Facilitate Post-Op Ligament Rehabilitation

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ABSTRACT

Using novel sensor technology to monitor a knee's health, one can measure the state of a post-op patient's knee unobtrusively, quickly, and accurately. A pair of Inertial Measurement Units (IMU) is coupled with a modern microcontroller, with the goal of the project being to create a device to use in an office setting. The device provides a quantitative output that can be used for plotting ligament recovery over time without the use of x-rays, thereby allowing a physician to prescribe and dynamically modify a rehabilitation schedule based on the individual needs of the patient.

I. INTRODUCTION

Ligament injuries in the knee are a common injury among athletes and active people, with about 275,000 ACL & PCL injuries each year requiring surgery[1][2]. Post-op patients usually require 6 weeks of intensive rehabilitation. Every patient is given the same rehabilitation schedule. Upon completion of the rehabilitation routine, patients are discouraged from engaging in vigorous activity for 6-12 months to monitor if complications arise [2]. This broad timeframe is due to the lack of an important diagnostic tool in determination of knee kinematic restoration.

The inability to measure the knee's health as rehabilitation occurs forces physicians to prescribe exercises and timeframes which might be redundant if the patient has healed sooner than the worst case scenario. This causes most patients to undergo unnecessary rehabilitation, which may increase costs.

II. METHODS & MATERIALS

A. Design

The knee goniometer device consists of two circuit boards, each of which contains a 3 axis accelerometer and one 3 axis gyroscope, which utilize MEMS technology, to measure the angle of the tibia in relation to the femur. The IMU boards will be mounted onto a knee cuff by Velcro and will be connected through UART (universal asynchronous receiver/transmitter) to the starter kit.

Fig. 1. Starter Kit Prototyping device

Fig. 2 & 3. Opposite sides of the same knee cuff, showing optimal placement of the 2 IMU boards, shown at right

B. Engineering Principles

The following images illustrate the matrix computation required for determination of knee kinematics:

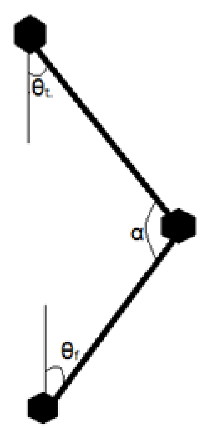

Fig. 6. A free body diagram of a knee where θt is the between the ground and thigh, θf is the angle between the ground and the femur.α is the calculated knee angle based on θt and θf.

Because the orientation of the attached sensors can vary from person to person, the vectors associated with each sensor during calculation would be different. Calibration of the device is crucial to obtaining precise angles, and is therefore done at the beginning of every test, even when testing the same patient on two separate occasions.

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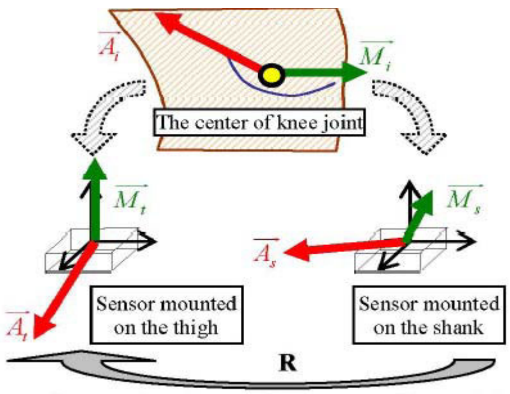

Fig. 5. Rotational matrix and vectors from the knee center

To align the vectors obtained with the shared axis (For example: y –with reference to rotation)
1. Rotate matrix to bring vector in xy plane
2. Rotate matrix to bring vector along y axis.
3. Rotate matrix about y axis.

Each position matrix is acquired from the IMUs, and is used to determine the Euler angle (θ) that represents rotation about the transverse axis. This angle is calculated by combining the value of corresponding element from the rotational matrix and equating it to the Euler sequence.

(1)
$$R_{DCM} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}$$

$$R_\psi^Z R_\theta^Y R_\varphi^X = \begin{bmatrix} \cos\theta\cos\psi & \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi & \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi \\ \cos\theta\sin\psi & \sin\varphi\sin\theta\cos\psi + \cos\varphi\cos\psi & \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi \\ -\sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{bmatrix}$$

By combining (1) and (2), we get

$$\theta = \sin\text{-}1(A_{31}) \qquad (3)$$

Let the given angle obtained from IMU1(placed on tibia) be θ_t and any given angle obtained from IMU2(placed on femur) be θ_f. To get the knee angle of a single axis, α is determined from the IMUs by subtracting the angle around the transverse axis of femur from tibia.

$$\alpha = \theta_f - \theta_t \qquad (4)$$

This process is repeated for the remaining 2 axes.

C. Testing

i. "Pegboard" Test

A "Pegboard" test was used to test verify measured knee angles were consistent with expected values. A pegboard was positioned in a stable configuration with the completed setup attached to two holes of the pegboard using peg hooks, simulating the position of a tibia and femur. The knee angles calculated by the Starter Kit were compared to the angles measured using the pegboard holes as references. The results were plotted in Excel, and in order to address pass/fail criteria, a t-test was used with a confidence level of $P<0.05$.

III. Anticipated Results

i. "Pegboard" Test

The anticipated results of comparing values obtained from the pegboard test with the values from the knee goniometer device were that the two sets of values were identical in that they gave the same outputs. These set of values would differ from patient to patient depending on the size and body mass exerted on the knee. The following Fig. 6 shows the anticipated knee angles from the device during a normal gait cycle.

IV. Discussion

This device has the ability to measure knee angle accurately. This would allow for a physician to prescribe a more personal rehabilitation plan, and give a better prediction of the patient's ability to return to vigorous activity. More importantly, the device can save the patient considerable time and cost by possibly reducing the period of rehabilitation. By being able to accurately measure knee angle, ligament health can be evaluated inexpensively and quantitatively in an office setting.

Acknowledgements

The team would like to acknowledge and extend thanks to Dr. Antonio Valdevit and Dr. Jack Andrish for their support and guidance with this project.

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