3D description of knee movements with a two IMU based wearable device: CHAKAMO

Ledezma MR. [1], Santos D. [1 - 2], Simini F. [1]
[1] Núcleo de Ingeniería Biomédica, Universidad de la República, Uruguay, rledezma@fing.edu.uy
[2] Departamento de Rehabilitación, Hospital de Clínicas, Universidad de la República, Uruguay

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1. INTRODUCTION

After a knee injury, rehabilitation is important because it will determine the evolution of the knee joint and its continuous improvement. To evaluate this improvement, the physiotherapist acts subjectively and uses tools such as goniometers to estimate ranges of knee angles. With these manual tools, the correctness of measurements depends on the instrument in use and on the physiotherapist's experience and ability. These factors can lead to an incorrect evaluation and therefore to a delayed knee rehabilitation evolution and can lead to a sub-optimal patient satisfaction. In addition, these measurements are made in a static position, whereas it would be important to estimate the functional activity of the knee so as to return it to normal.

There is therefore a need of an instrument for clinical use that would estimate the joint kinematics of the knee during a functional task. The first work was carried out based on two orthogonal cameras to calculate the 3D position of markers in space [1], but the skin movement at the markers site precluded the method to correctly model the movement of the knee. The two cameras approach was abounded as a non-precise enough method [2]. For this reason, the main idea of this work is to design and implement a device for clinical use with two inertial sensors, one on the shank, one on the thigh, to estimate knee joint kinematics. Inertial sensors were selected because they allow for natural movement and therefore measurements can be taken in any working environment. In addition, the protocol we set ourselves to develop, to quantify joint kinematics, should be short and straight forward for the physiotherapist. The objective of the paper is to describe a novel design of an instrument, CHAKAMO, which produces time graphs to report flexion-extension as well as rotation of a person performing a simple motor task, climbing on a chair, as shown in Fig.1.

2. MATERIAL AND METHODS

The design of CHAKAMO includes the inertial sensors that were selected based on the angular velocity of human knees, the possibility to engineer the knee joint movement measuring device and standard communication with computing elements. The knee joint movement captured is to be shown on a display either in 2D time series or 3D bone dynamic representation. Calibration is necessary to adapt the measurement to every circumstance and patient. To calibrate, data acquisition was carried out and the sensor fusion algorithm executed to quantify the movement of the two fixed segments, tibia and femur.

Motor Task

The motor task consists of stepping up and down a step with one leg. Fig. 1 shows a chair taken as a high step (50 cm). The cycle begins with the knee under study flexed and the foot resting on the step. Then the subject proceeds to full knee extension lifting in the air the other foot. The movement must be natural and the participant is asked to return to the first position as soon as full extension is reached. When the contralateral foot returns to the floor, one cycle is completed. This task is functional and includes all movements of the knee, therefore it is possible to estimate the flexion and extension, as well as the rotation of tibia with respect to femur.

Inertial Sensors

Joint kinematics can be determined by sensors that have 3D accelerometer, gyroscope and magnetometers, along the three Cartesian axes of movement. The sampling frequency of the sensors must allow the representation of the motor task: being the motor task of a low frequency, an appropriate sampling rate is between 50 - 100 Hz [3][4]. The adopted sampling rate of 100 Hz accurately estimates the complex 3D joint movement. In addition, the sensors must have a wireless data communication method, a rechargeable battery and the ability to extract data from the sensor using software support, for instance Python programming. The MetamotionR sensors (MBI-ENTLAB, San Francisco, USA) have these characteristics. They are priced around $100 each.

3D Model and Calibration

The multibody kinematic model refers to a set of rigid bodies connected by joints [5]. These rigid bodies usually have 6 degrees of freedom (DoF): 3 angular DoF and 3 displacement DoF [6]. For the present study, a 3 angular

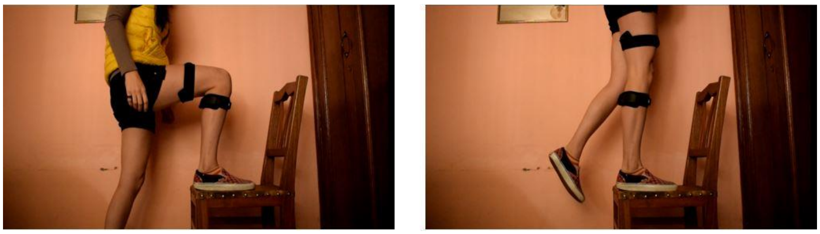

(a) (b)

Figure 1. Motor task (a) Start of the cycle with 90º knee flexion. (b) Full knee extension, half cycle.

DoF model is used. For the model, the axes of the sensors are taken as the axes of each lower limb segment. The sensors obtain the data according to a global coordinate system. As each sensor has its own reference system, it is necessary to calibrate the inertial system to the body system [7].

To define any joint movement, two sensors are necessary one for each segment of the joint: femur and tibia segments to study knee kinematics. Both sensors must be expressed with a time-invariant relationship between the inertial coordinate system and the body coordinate system that is assumed to be embedded in the bone. This operation is called sensor-to-segment alignment. [8]. This alignment is based on the representation of 3 axes for the femur and 3 axes for the tibia. Subsequently, 3 axes will be selected to represent the joint coordinate system. For simplicity, in this project, manual calibration is performed manually placing the sensors orthogonally to the bone inside elastic bands on the thigh and the leg.

The static calibration method consists of asking the subject to stand with her/his arms at the sides of the body and with the foot to foot distance equivalent to the shoulder of the subject, for 10 seconds. This yields the gravity vector of both sensors which allows to align them. We have adopted a combination of the static calibration with the manual calibration [9]. This calibration model is based on [7] but without the functional stage. The decision was taken to adopt a method that could be performed at home depend on an expert physiotherapist to perform the movements of each joint and that there are not compensations with other joints.

Fusion Algorithm and 3D Knee angle measurements

Inertial sensors present difficulties since they do not provide a direct measurement of the physical quantity of interest, this is because their sensor fusion algorithms only estimate the orientation of the segments in which they are attached. A procedure called fusion is therefore necessary and joint measurement relies on an appropriate fusion algorithm. In addition, no fusion algorithms prevails and the algorithm of choice depends upon the application [10].

The sensor fusion algorithm used is that of Madgwick. [11]. This filter is based on compensating for the magnetic disturbance and subsequently for the gyroscope bias that increases over time. It was observed that this filter works well in real-time applications due to the computational load and also works well in low-frequency applications. These parameters are suitable for the clinical use instrument to be developed.

By fusing the data from sensors, the orientation of the thigh and the orientation of the shank are found with respect to the global system. Therefore, to obtain knee joint data, these two measurements must be combined. It is known that the movement of the joint is defined by the orientation of the distal segment relative to the proximal segment. By performing the multiplication of quaternions, it is possible to obtain the movement of the joint [10]. This will be represented in terms of quaternions, then the transformation to Euler angles is carried out to show angle time series, readable by the physician or physiotherapist, and stored in the Electronic Clinical Record.

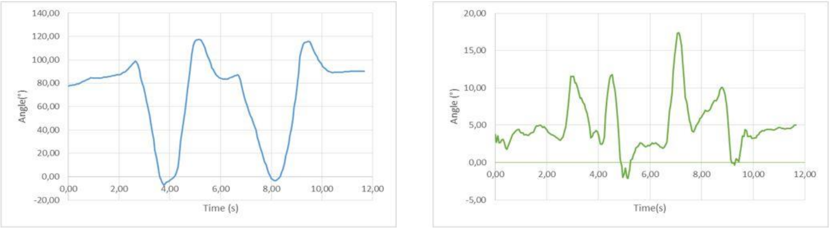
3D Movement Description by Ursina engine

After obtaining the data in Euler angles, CHAKAMO displays them: we first obtained time series of flexion extension and rotation angle for the longitudinal segment of femur and tibia. At time t=0 the two bone models adopted spatial orientation given by the initial calibration. As time elapses, the 3D movement of the bones is reconstructed and shown in the time graphs. As first approximation, the distal extremity of the femur is made to coincide with the proximal extremity of the tibia. During representation of the motor task, the bone models are seen on the monitor following in real time the movement of the subject wearing the IMUs.

We used Ursina engine within Python in Anaconda [13], which is a platform for game development for Python [14]. This engine allows to import 3D models from Sketchfab page [15] and use them freely, giving models of the human femur and tibia. During the visualization of the bones, the Blender tool [16] was used to reduce the size of the model since it includes unnecessary details in the modeling. The movement of these segments was programmed to be seen on the monitor using fusion data, as see in Fig 3.

3. RESULTS

After obtaining the data from the sensors and fusion using the Madgwick algorithm at a rate of 100 Hz, Fig. 2 shows rotation and flexo extension of the knee during the motor task performed by a healthy subject. In Fig. 2a



(a) (b)

Figure. 2 Knee kinematics quantification during 2 cycles (a) flexion & extension (b) Internal & external rotation

two cycles of the motor task are observed: the cycle begins with a knee flexion of 77º which increases due to the necessity to propel the leg to climb the 50 cm step. Next, the flexion abruptly declines at time=3.75s to -7º degrees in a hyper extension, which indicates that the subject is at the highest point of the motor task, i.e. standing on the chair. Then comes a knee flexion culminating the first cycle at 6.11s. Then the second cycle starts. The range of flexion extension is of the order of 125º. In Fig. 2b the rotation movement is observed, which has a much smaller range of motion, of the order of 20°. In Fig. 2b, two peaks are observed in each cycle, which means that there is a greater rotation when the knee is in flexion. With the orientation axes coordinates time series, we programmed the 3D representation using Ursina engine. Table 1 shows the sequence of selected angles during the motor task.

Table 1. Knee measurements during the stages of the motor task

Motor task instant	***Time (s)***	***Flexion Extension (º)***	***Rotation(º)***
0%	0.00	77.75	3.74
25%	2.80	91.12	6.33
50%	3.75	-7.19	3.53
75%	5.10	117.19	-2.03
100%	6.11	83.48	2.53

Fig. 3 shows four images taken during a real time capture of the movement of the femur and tibia of the subject during the motor task at 0%, 25%, 35% and 50% of the cycle to account for stepping up. As the sensors are not located directly inside the bones nor affixed to them, a previous calibration was carried out to place the bones in an initial position. Then, as the femur and tibia move, a trigonometric relationship is solved to position the models with each other, considering that the available data are the midpoint of the bones. This positioning insures that both bones meet at the knee joint. The 3D knee dynamic representation is a supporting evidence for clinicians.

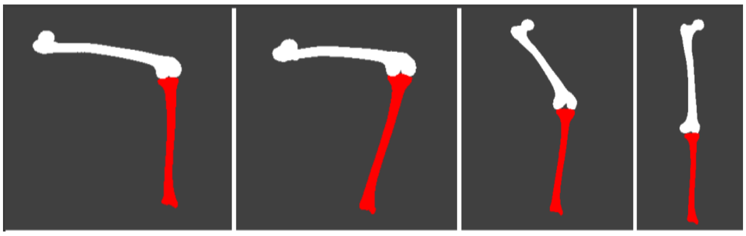


Figure 3. 3D representation of the movement of the knee at 0%, 25%, 35% and 50% of stepping up.

4. DISCUSSION

During the development of a new instrument, CHAKAMO, we have selected inertial sensors due to the easy application and use by physiotherapists. Manual alignment and static calibration were decided so as to insure that the device would be independent from the acting physiotherapist. A correct dynamic calibration would require immobilization of the hip, a maneuver our estimation method does not include. An incorrectly performed dynamic calibration would produce errors in the quantification due to false movements of the joints.

Normal tibial rotation accounts for approximately 25° [RISTANIS] during climbing a step and our preliminary measurements of 20° are compatible and of the same order of magnitude. After total knee replacement (TKR), Leardini and coworkers [17] have published much lesser rotation ranges in a group of operated on patients: less than 10°. CHAKAMO has the potential to measure 3D movements of the knee for these medical conditions.

Considering the anatomy of the knee, rotation is possible as the knee is not locked when in full extension, allowing rotation movements. The clinical relevance of CHAKAMO consists in allowing an easy a real time evaluation of axial rotation during either open chain or close chain movements. Ristanis has established that ACL reconstruction may not be successful in restoring pre lesion rotation range [18], a condition that CHAKAMO can document.

We have chosen Madgwick algorithm to obtain the fusion of raw data into the three angles of each segment. As a consequence of using the magnetometer data, Madgwick algorithm [10] gives good results provided no ferromagnetic elements are located nearby, because they affect the sensors sensitivity and measurement precision. Kalman filter [19] can also be utilized to obtained fusion parameters starting from sensors raw data. Data processing in this case differs from the Madgwick case. Albeit the Madgwick algorithm produces correct fusion directions, the Kalman filter can also be used for movement analysis. To decide which method to follow, we will also use a Kalman filter as sensor fusion. We will notice the difference in the application of both algorithms.
As a document of exploration of the 3D movement of the knee during specific motor task, a clinical report will be generated with normal values based on averages of motor task cycles. This report will include rotation and flexion extension ranges of the affected limb along with the contra lateral limb. Clinicians will then have a clinical document to put in practice recommendation made and to monitor joint kinematics during follow up.

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