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Published version

NWAIZU, Harriet, SAATCHI, Reza and BURKE, Derek (2016). Accelerometer based human joints' range of movement measurement. In: 2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP). IEEE.

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Accelerometer Based Human Joints' Range of Movement Measurement

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Abstract— Accurate measurement and analysis of joints' range of movement (ROM) are important for assessing joint related health conditions and are valuable to clinicians for diagnostic and rehabilitation purposes. As an alternative to using the camera-based methods which are restrictive and expensive, and the electro-goniometers which are not sufficiently effective in some scenarios, researchers are developing the use of microelectromechanical devices such as accelerometers for measuring human joints movement. This paper presents the development of an accelerometer based system to measure movement angle, velocity, acceleration and displacement for the knee.

Keywords—Accelerometer; Joint measurement; Human movement; motion analysis.

I. INTRODUCTION

Human movement analysis has been a subject of interest since the fifth century [1] and its still being explored by researchers and clinicians alike [2]. This extensive interest is due to its great potential in a variety of applications and in recent times, has played a major role in many health related applications [3]. Research has shown that the ability to monitor human activities that include, human activity recognition and joint angle measurement [4] can effectively improve the quality of healthcare provided to patients [5].

An important aspect of human movement analysis is joint angle measurement as this information is helpful in better understanding movement disorders, such as arthritis. Joint's movement measurement information can assist clinical diagnosis and rehabilitation. Arthritis, which is broadly classified into rheumatoid- and osteo-arthrisis, is a joint disease characterised by progressive degradation of the cartilage [6], the smooth material covering the ends of bones in the joints, that protects the bones from rubbing gainst each other and absorbing vibration shock during movements [7]. As this surface is damaged, it can cause joint inflammation, pain, stiffness or in a more chronic case, severe disabilities, which affect patients quality of life [6].

The focus of this study is in rheumatoid athristis which results in the joints being inflamed, and of the different locations of arthritis, the arthritis of the knee is one of the most disabling [6], hence ability to accurately measure a joint's angle of movements is important to providing a better healthcare to patients suffering from arthritis.

The conventional gold standard for measuring and monitoring general human movements including joints' angle is optically based. Its setup involves placing several cameras around a walkway, and reflective markers on the joints. As the subject moves, the system produces the 3D spatial movements of the markers, while a software determines an estimate of joints' angles or the gait parameters [8]. However, this approach is restricted to monitoring in specific gait laboratories as it requires an expensive set up and so it is not very practical for routine clinical use or assessment of patients activities in their home environment. An alternative method for measuring joint angles range of motion is with electrogoniometers. However, this approach requires a trained clinician to operate, it is time consuming to perform and is not sufficiently robust for daily clinical use [4, 8].

To overcome these limitations, researchers have been exploring alternative methods of measuring joint angle. Recent developments in micro-electromechanical systems (MEMS) have resulted in portable, relatively affordable and wearable sensors such as accelerometers, gyroscopes, magenetometers. These can be used either individually or they can be integrated into a single chip as an inertial measurement unit (IMU), for measuring movements in three orthogonal axes, typically referred to as x, y and z. Extensive research has been carried out in developing these sensors as they have the potential to provide more practical solutions for clinical use and for patient’s movement monitoring in their their home environments.

The challenges in using accelerometers and gyroscopes are computational problems for determining the angles [8] also, the effect of offset errors on gyroscope's output as a gyroscope provides rate of rotation and integration of its output is needed to determine the amount of an object's rotation. [9].

Willemsen et al. [10] used eight uniaxial accelerometers to determine knee angle without the need for integration, so as to reduce the effect of ofset drift. Kurata et al. [11] monitored upper limb motion -elbow and shoulder joints- in daily activities using two accelerometers set at “both-near-sides” around the joints and they concluded the system was effective for one axis motion monitoring, though the accuracy of the three axes joint movement was not confirmed in the study.

Djurić-Jovičić et al. [8] used accelerometers to estimate absolute segment and joint angles during gait in the sagittal plane, with focus on the knee and ankle joints based on a second-order low-pass digital filter, to reduce the effect of drift on the results. The effectiveness of the system was compared with the results obtained from flexible goniometers. They obtained a root mean square error (RMSE) of 6° for the knee and 2° to 4.7° for the ankle joints.

Dong et al. [12] used four biaxial accelerometers to measure flexion-extension angles, however the accuracy of system was dependent on the sensors being placed parallel to the sagittal plane.

Other researchers have also considered the use of IMUs for measuring joint angles. Bakhshi et al. [4] focused on measuring knee joint range of movement using two IMUs placed near the joint. Bennett et al. [13] developed an algorithm to measure knee angles using two IMUs and artifitial neural networks. Their system was validated aganist the results obtained from an electro-goniometer.

In this study 3 axes accelerometers were investigated to measure knees' angle, velocity, acceleration and displacement.

II. JOINT ANGLE MEASUREMENT

Joint angle in one plane has been measured using a number of formulae. Some of these are explained below.

A. Method I for Joint angle Measurement

In a study, a method for measuring a one axis joint movement of the elbow or knee was developed [11]. Fig. 1 shows their representation of the accelerometers placements near the elbow joint, where a and *a'* are accelerations load on accelerometer 1 and 2 respectively.

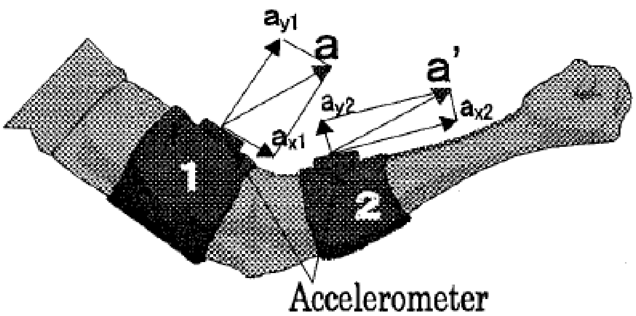

Fig. 1. Accelerometers placed around joint for measuring elbow motion [11].

The acceleration components of the two accelerometers in the x and y directions are represented as (a_{x1}, a_{y1}) and (a_{x2}, a_{y2}) respectively. The algorithm developed for measuring the joint angle (ϕ) is based on the principle of rotation matrix. After simplifying the matrix, equation (1) is obtained.

$$\tan(\phi) = (a_{x2}.a_{y1} - a_{x1}.a_{y2}) / (a_{x1}.a_{x2} - a_{y1}.a_{y2}) \qquad (1)$$

B. Method II for Joint Angle Measurement

According to the study by [4, 8], joint angles can be determined by subtracting absolute angles of the neighboring segments. Therefore to find the angle of a knee joint (ϕ_{knee}), the angles for the absolute segments are initially computed, i.e. the angles referenced to the gravity for the thigh (ϕ_{thigh}) and shank (ϕ_{shank}). The angle from the accelerometer placed on the shank is then subtracted from that placed on the thigh.

$$\phi_{\text{knee}} = \phi_{\text{thigh}} - \phi_{\text{shank}} \qquad (2)$$

C. Method III for Joint Angle Measurement

In [14], an algorithm was also used for calculating the angle between two accelerometer readings. The principle employed was based on vector algebra, which provides a means of calculating the angle change α of the apparent gravity vector between any two accelerometer readings (a_x, a_y, a_z and b_x, b_y and b_z respectively) as shown in (3).

$$\cos(\alpha) = \frac{a_x b_x + a_y b_y + a_z b_z}{\sqrt{a_x^2 + a_y^2 + a_z^2}\sqrt{b_x^2 + b_y^2 + b_z^2}} \qquad (3)$$

In this study method B was used as it gave closest angles to those measured by a goniometer.

III. METHODOLOGY

In this section the set up used to record the data and procedure for their analyses are explained.

A. Experimental set up

Two tri-axial accelerometers boards (ADXL335 from Sparkfun) with dimensions 4 mm × 4 mm × 1.45 mm were used for the experiments. The ADXL335 measures acceleration with a minimum full-scale range of ±3 g [15]. These units were connected to the Arduino Mega 2560 microcontroller board, which in turn was connected up to a computer with USB. The microcontroller board digitised the analogue x, y and z signals from the accelerometers for display, storage and processing by the computer. The recording sample rate was 98 samples/second.

A joint was initially modelled as shown in Fig. 2. to perform a controlled movement and angle measurement experiment.

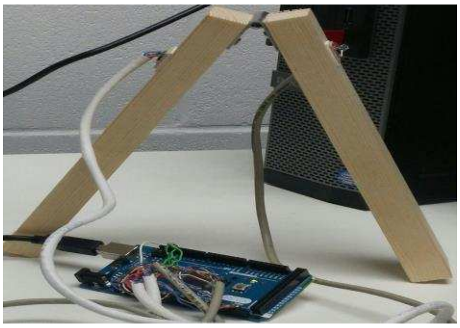

Fig. 2. Basic knee model showing the accelerometers locations

The model consisted of two wooden bars of the same dimension jointed by a hinge. The sensors were attached to the bars using double-sided adhesives. This provided a very simple model of a situation that accelerometers are attached to the right and left human thighs and shanks with the aid of straps with positions shown in Fig. 3. In this figure, α is the angle of inclination of the thigh, β is the angle of inclination of the shank and ϕ is the relative angle of the knee joint.

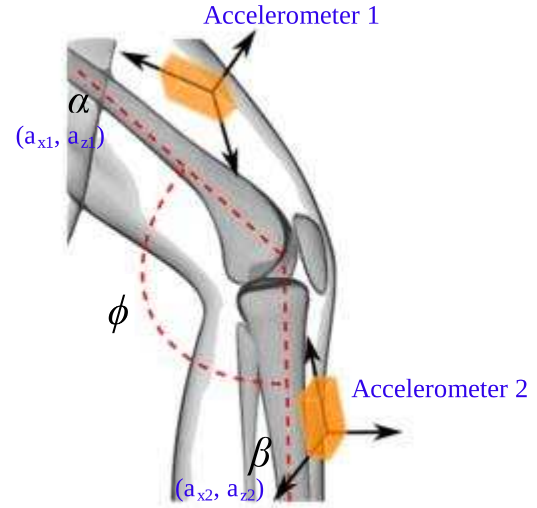

Fig. 3. Relevant movement angles α, β and ϕ [16].

In the latter part, experiments were performed with the sensors attached to both right and left thighs and shanks of a subject who sat on a chair and moved his lower legs up and down freely and simultaneously. The movements' angles, angular accelerations, angular velocities and total angular displacement were calculated from the accelerometer readings that were recorded, analysed and compared.

B. Procedure to analyse the accelerometer signals

The values of α, β and joint angle ϕ respectively were calculated as

$$\alpha = atan2\ (a_{x1}/a_{z1}) \quad (4)$$

$$\beta = atan2\ (a_{x2}/a_{z2}) \quad (5)$$

$$\phi = 180 - (\alpha + \beta) \quad (6)$$

where a_{x1} and a_{z1} are the acceleration measures for the x and z axes of the accelerometer attached to the thigh, a_{x2} and a_{z2} are the acceleration measures for the x and z axes of the accelerometer attached to the shank as shown in Fig. 3.

Once the joint angle was determined, the angular velocity (v), angular acceleration (a) and total angular displacement (d) were obtained using equations 7, 8 and 9 respectively. The velocity gives a measure of how fast the leg is swinging; the acceleration measures changes in the velocity of the swing; and the displacement shows the total movement made by each leg. These results were compared for both right and left legs to determine movement pattern differences.

$$v(t) = \frac{d(\phi)}{dt} \quad (7)$$

$$a(t) = \frac{d(v)}{dt} \quad (8)$$

$$d = \int_{t=0}^{t=T} v(t) \quad (9)$$

where T is the signal recording duration

IV. Results and Discussions

For validating of the angle measurement by the accelerometers, a flexible goniometer was used to measure the actual angles from the knee model (shown in Fig.2). The results are plotted in Fig.4. The accelerometers were able to track the angles as measured by the goniometer. The joint swung in the range of 90° and 170°. The accelerometers' measured angles confirmed to the goniometer readings.

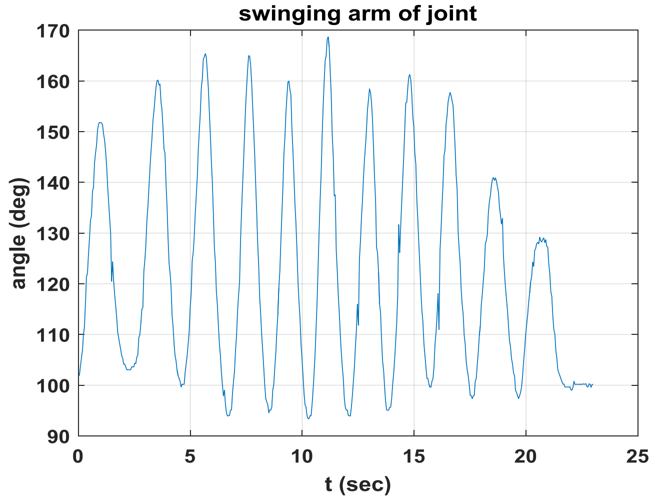

Fig. 4. Angles measured using the accelerometers

Plots for angle, angular velocity, angular acceleration and angular displacement are shown in Figs 5 and 6. It was observed that the movement patterns have distinct differences.

Figs 5b and 6b, show zoomed sections of the plots indicating the relationship between the angles, velocities and accelerations respectively (indicated by the black line running through the graphs). It can be seen from the figures that when the angle peaks (state of rest), the velocity is zero which indicates no movement at that time, and the acceleration peaks as well due to the sudden change of positon (i.e. when it starts to go to next swing).

The left leg covered a wider range of angles approximately 102.14° than the right leg which covered a range of approximately 80.23°, which explains the lesser distance covered by the right leg.

The maximum velocity of the left leg in the positive direction was about 2.98 rad/s which was higher than that of the right leg of about 2.35 rad/s.

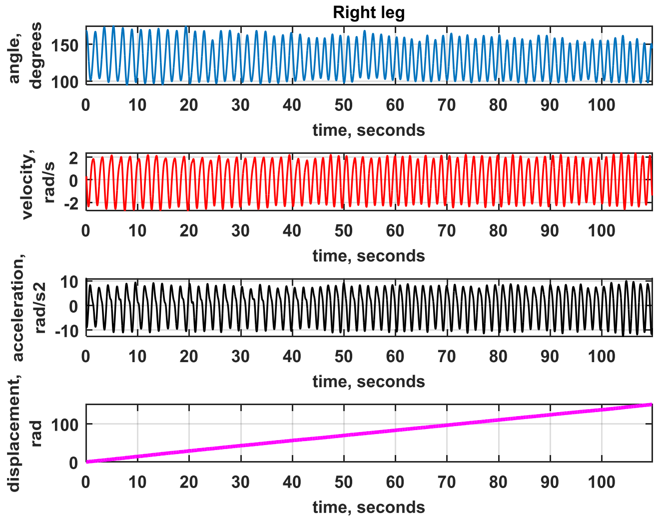

Fig. 5a. Measurements from the right leg

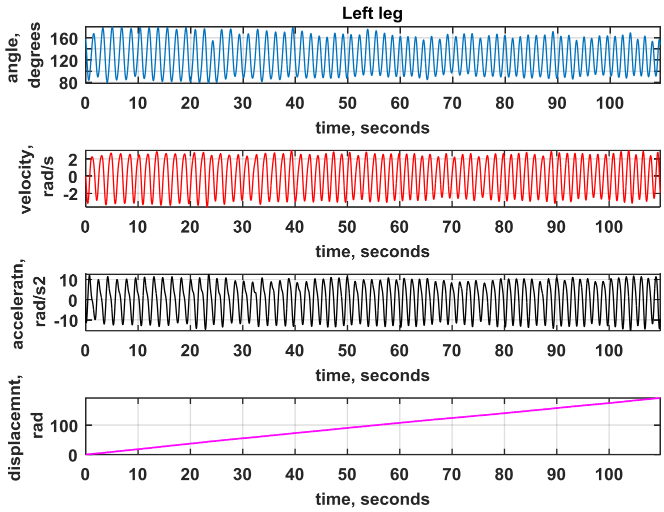

Fig. 6a. Measurements from the left leg

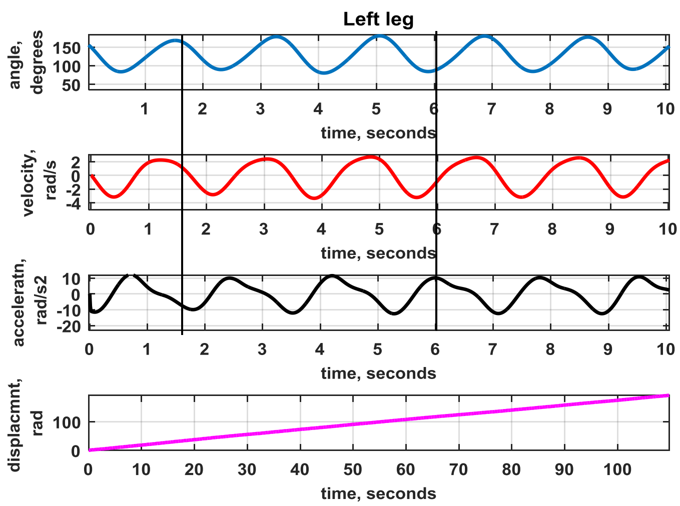

Fig. 5b. Measurements from the right leg (zoomed in plot)

The histograms of the data are shown in Figs 7 and 8 which provide further information about how the left and right legs differ.

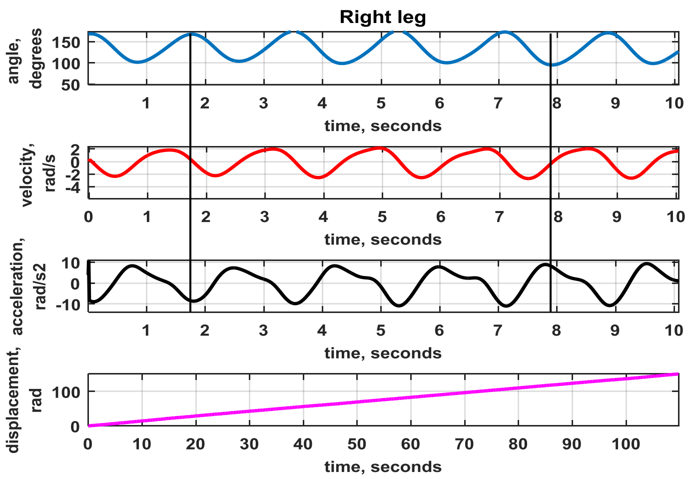

Fig. 6b. Measurements from the left leg (zoomed in plot)

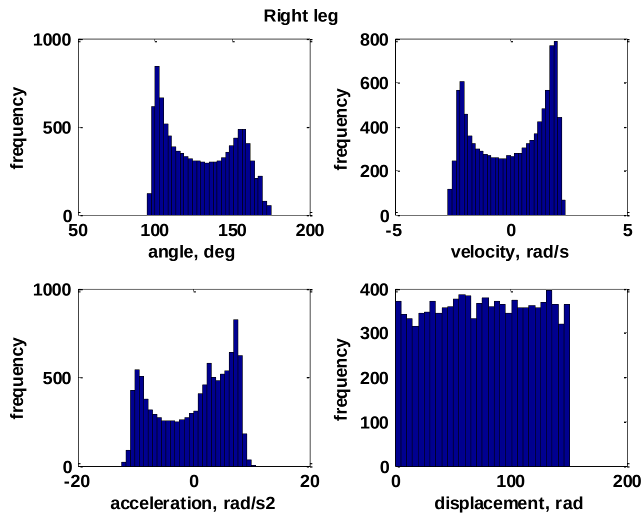

Fig. 7. Histograms of data for the right leg

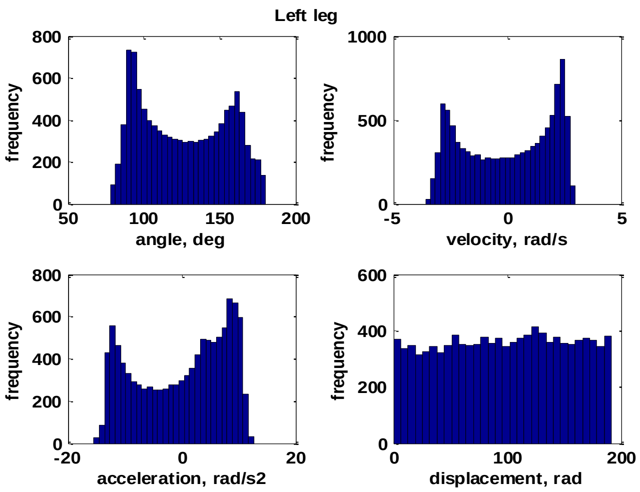

Fig. 8. Histograms of data for the left leg

Fig. 9 shows that the subject is able to move the left leg swifter and to a wider angle than the right leg. Also, the velocity and acceleration are higher in the left leg than the right leg.

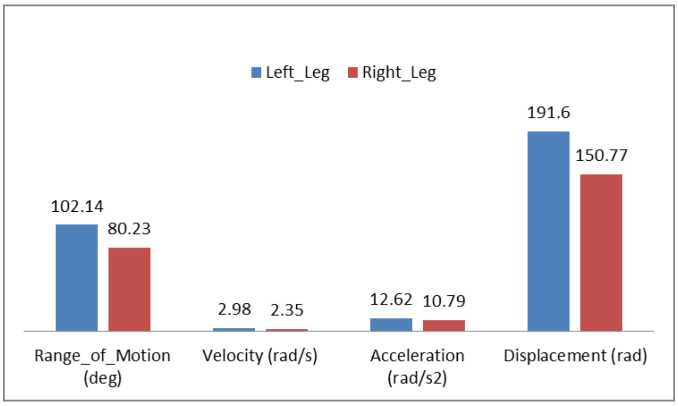

Fig. 9. Comparison of data obtained from both legs

The symmetry information in the leg movements determined by skewness is summarized in Table I. The largest difference is observed for the acceleration.

TABLE I.

	Skewness of the right and left legs			
	Angle	Velocity	Acceleration	Distance
Right	0.1462	–0.1577	–0.2964	–0.045
Left	0.1199	–0.1754	–0.3302	–0.0166

The short time Fourier transform (STFT, also known as spectrogram) of the angular displacement for each leg was also obtained to determine the time-frequency relationship of the leg swing and the extent of movements over time. These are shown in Figs 10. The plots show initially (upto 40 seconds), the legs moved at a slower rate (about 0.555 Hz) but the extent of movement (indicated by the magnitude) was higher. Thereafter the legs swung at a higher rate (about 0.65 Hz) but at a lower extent (again this is indicated by the magnitude of the plot).

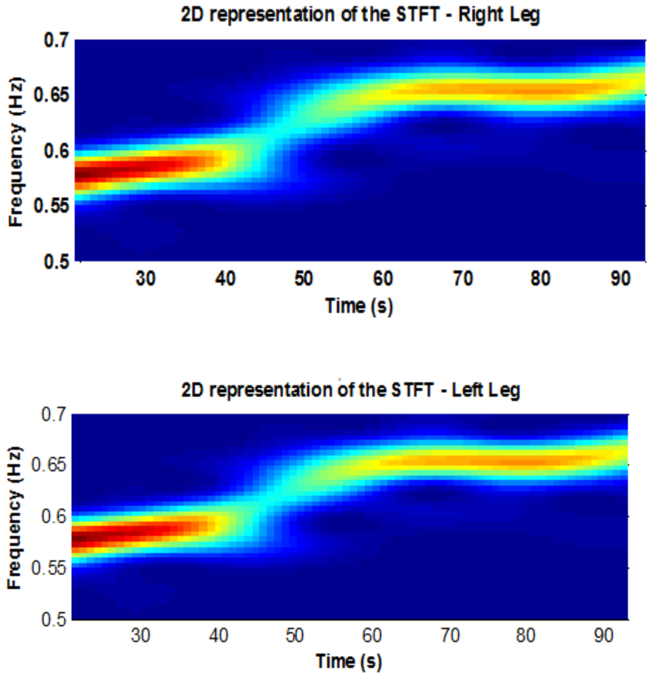

Fig. 10. Short-time Fourier transform of the angular displacement for the right leg (top) and left leg (bottom). Higher amplitudes are shown in bright red up to 40 seconds and the yellow colour thereafter shows a reduced relative amplitude.

V. Conclusions

A system to measure the joint range of movement using accelerometers was developed. The sensors were used to collect movement data from the legs of a normal adult subject while he sat on a chair and moved his legs simultaneously up and down to their full extension and flexion. The movement angles, accelerations, velocities and total displacement were determined. To verify the angles calculated, a goniometer was also used to measure the angles obtained from an experiment performed using a very simple model of the knee.

The results obtained showed a good tracking of the angles from the knee model. The movements made by the legs were compared. The results indicated that his left leg swung slightly higher and faster than his right leg.

Further work will be to take this project to a hospital to use the system for comparing the symmetry of the human joints and also to analyse joints movement patterns.

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