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Design, implementation and validation of a low-cost electrogoniometer for measuring range of movement of different human joints in movement analysis.

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Contents

Abstract

The project consisted of the hardware and software development from scratch of a low-cost Electrogoniometer for the kinematic analysis of the range of movement from the different joint angles of the body. It was also made a validation of the system and a real-world medical case study with arthrodesis patients.

The hardware used on the development of the prototype were both Arduino MKR1010 and MPU6050 and the acquisition and the signal-processing software was made on python. Three different tests were performed. The first one was aimed to get the first contact with the system and to prove that the model was viable. Once this was done, the second test was performed. This one consisted of the validity of the prototype with elbow healthy samples. Finally, the prototype got involve on a clinical case study as it was used on the evaluation of the range of movement of arthrodesis patients which were compared with healthy subjects. For the validity, the EG signal was compared with the goal standard and validated system Kinovea. The two statistical methods that were used were the mean distance between peaks and the RMSE.

The main result was the error obtained which was of $\pm$ 2.86º out of a 0º to 140º range of movement. This result compared with the acceptance error of $\pm$ 11.5º from the last review and validation of the classical goniometry is a satisfactory result.

Keywords:

Electrogoniometer, Inertial measurement Unit (IMU), Accelerometer, Gyroscope, Arduino, Low-cost

Introduction

Motivations

The idea from this project came after getting to know all the instrumentation and sensors that are available in the Biomechanics Laboratory from Universitat Rovira i Virgili placed in Hospital Sant Joan de Reus during my first internship, my main function was to co-develop and validate a system to synchronize all the commercial devices (BTS Bioengineering) in the lab. Those devices were surface electromyographer, inertial sensors, that includes accelerometers and gyroscopes, and a force platform.

After achieving that objective, in my second internship, I went deeper on Inertial Measurements Units (IMU) sensing. The objective was to create and validate an electrogoniometer based on both BTS accelerometers and gyroscope. A different synchronization between all the data had to be done because of a hardware limitation of this device. The cost of this implementation is overmuch for some investigators that do not have the IMUs previously.
That's the reason why I decided to focus this project on making a low-cost generic electrogoniometer that achieves the commitment between accessibility and precision.

State of art

Electrogoniometers (EG) are widely use by physiotherapist as it is a more accurate and confident approach to the classical goniometry or clinometer (see figure 1), which has been used for many years to observe the joint angle of the different articulations [1], [2].

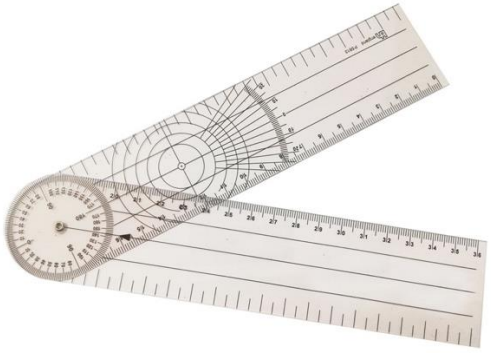

Figure 1. Classical goniometer. [3]

The classical approach has two important issues, first one is related on the accuracy of the human eye when extracting the angle of the goniometer. The other one is that clinicians need three tools to assess all human joints, the classical goniometer, a clinometer to spine and special fingers goniometer to adapt to little arms. On the other hand, the price of this medical instrument is very low as a goniometer can cost from two to ten euros. A more precise alternative for goniometry in the current market are for example the digital ones [4]. This model, which cost approximately a couple of tens, solves the inaccuracy on the interpretation of the angle obtained by the goniometer. However, it also has the possible error of placement.

The next step in accuracy for joint measurement comes with the electrogoniometers (see figure 2).

Figure 2. Electrogoniometer from Biometrics ltd [5]

The two main issues from the classical goniometry are solved in this model, but the price has an exponential growth, as many electrogoniometers are above the hundred euros. [5], [6]. It also has a negative aspect as the majority of the commercialized EG are specially done for a unique joint e. g. Biometrics ltd electrogoniometer for ankle or fingers. [5].

It is known that EG can be recreated as the union of some IMUs by extracting their orientation, this feature of the IMUs is a long-time application of this electronic component [7]–[12].

The majority of the electrogoniometers on the market are very expensive and are not suitable for independent physicians. Also, the possibility for a non-engineering investigator of making a self-made electrogoniometer based on commercial IMUs are still very expensive as some of them cost between 1440€ (Biomap) to 3900€ (BTS).

Before using any IMU device a calibration must be performed, this is usually done in horizontal and stable position, for example with the IMU laying on the table. [11], [12].

In medical applications, this ideal conditions for calibration are not suitable for the biomedical application, as the body is not a perfectly flat surface, is in constant movement e. g. (breathing or muscle tightening) and, most important, almost all the surfaces of the body are perpendicular to the floor when standing, which is how mostly all the clinicians register daily living activities including gait, run or jump.

This implies that the gravity component is not on the Z axis (the normal one) [11], [12]. This gravity variation is not as simple as rotating the sensor, a full rotation transformation matrix [13] must be performed.

Once the calibration is made, almost all the references found, computes the gyroscope angle and then the accelerometer's angle, finally most of them solve the fusion sensor algorithms of the results with either the complementary filter [11], [12] or the Kalman Filter [8], [14]. Some other usual limitation of the IMU-based EG is that are commonly made for measuring unique movements. [14]–[17].

Objectives

The main objective of this final degree project is to fully develop from scratch a generic low cost Electrogoniometer useful for all the peripherical joints of the human body. The different secondary objectives are:

1) The hardware design which includes:
    - To design all the main electronical connections, which implies both soldering and implementing a user-friendly final product.
    - To build all the necessary components for attaching the Electrogoniometer to the human body.
    - To develop all the low-level C++ code of the microcontroller to get the data via the I2C bus.
    - To send all the acquisitions in real time via Bluetooth Low Energy.
2) The software implementation:
    - To develop a Python code that receives all the data and save it.
    - To develop a Python code that Preprocess it to obtain the angle of each component and sensor.
    - To develop a Python code that Process it with all the necessary correction until the final angle is computed.
    - To develop a user-friendly graphical interface for the physician to use the Electrogoniometer.
3) Validity and reliability of the prototype:
    - To validate and make a reliability test from Elbow joint in healthy subjects compared with a goal standard (Kinovea).
    - To test the Electrogoniometer on a medical application:
        - Healthy Ankle joint group.
        - Pathological Ankle joint group.

Methodology

Hardware development

Software development

Arduino
Python

Design of validity and test-retest

Study design

The study was a prospective observational study that was divided in three different orientations (HH, VV, VH), the order of the study also accompanies the development of the prototype as they are sorted by difficulty. The first one, the HH, implies the first touch with the project, it was made on an inert object (goniometer), then the VV study adds one more level of difficulty because of measuring the angles on the body which is in constant movement that will be detected and considered as noise. Then the last study is the harder one made as the angle measured was a three dimensional one, and a lot of noise is added since e. g. the heel strike affects the accelerometer approximation. Despite of that, all three studies could contribute to the successful development of the prototype.

HH study

The first one, the HH study had two principal objectives, the first one was to research and discover how to relate all the data acquired and transform it into an inclination angle and then into a joint angle. The second objective was to make the first contact with the clinical measurements.

Figure 24. Stable position of the goniometer on the table with both sensors fixed with tape on it. The fix arm was also adhered on the table.

The assembly consisted of putting the EG on top of a goniometer as seen in figure 24. The whole set up was on a totally horizontal table with one fix arm and a mobile arm, the initial position of the mobile arm was on 0º with a range of movement that could reach up to 170º. The maximum value was approximately 170º because of the physical impediment of the MPUs. The communication between the set up and the PC was made via the Serial monitor (USB) of the computer. The main difficulties faced during this study were to calibrate in a proper way, to find the relationship between both sensors and both IMUs. Both problems were solved as explained before. There was made 122 test that can be found on Annex 3.

Variables measured:

- The inclination obtained with the EG (Degrees).
- The inclination obtained with the goniometer (Degrees).

Acquisition procedure:

1. The EG was calibrated into a horizontal and stable position.
2. Three seconds were waited for the calibration part.
3. The first movement to the angle desired was made and then hold it for 5 seconds (Fig 25).
4. Then the mobile arm returned to the initial position of 0º.
5. All the data was then checked and evaluated with a MATLAB code.

Data analysis: A qualitative analysis of the curves obtained.

Figure 25. Mobile arm on approximately 45º of the table.

VV study

The VV test had three main objectives, the first one was to face the orientation problem, as both sensors were put in a vertical way. Then the next objective was to be able to make the study into the body, specifically in the arm. Finally, the main objective was to make the validity and the reliability of test of the sensor.

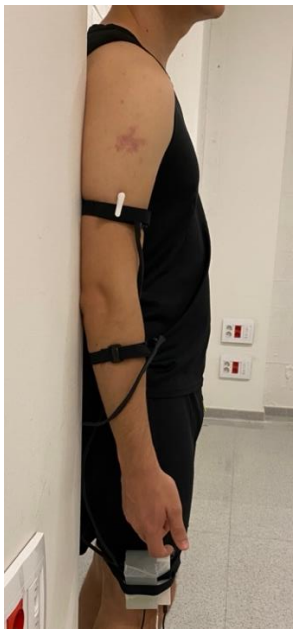

Figure 26. Initial stable position in maximum extension of the elbow.

The assembly can be checked in Figure 26, it consisted of putting one MPU into the arm and the other one equidistant at the forearm. The microcontroller and the mother boards

where outside the body and the communication between them and the PC was made by Bluetooth.

The main difficulties from this study were to face the body movement of e. g. bicep muscle contraction, and the behind-the-scenes calculus of the rotation matrices for the obtention of the inclination angle.

For this study, a total of 28 healthy subjects participated in two different days, having a test and a retest, so there were extracted a total of 56 signals. The test that was made consisted on making repeated elbow flexo-extensions (see Figure 27) from the maximum extension to the maximum flexion as shown in the right side of Figure 27. The movement was made at an approximately 60 bpm controlled by a commercial metronome. This criterion was named as the elbow method/criteria.

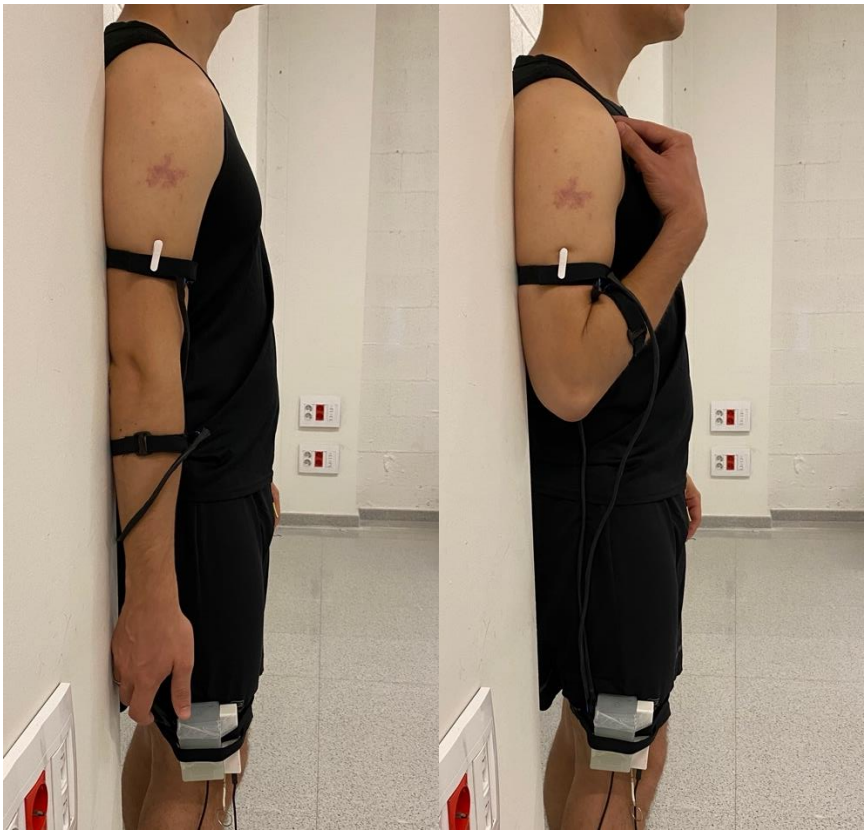

Figure 27. Flexo-extension movement, with maximum extension on the left side and maximum flexion on the flexion.

Variables measured:

- The angle of the elbow's flexo-extension and varus-valgus obtained with the EG (Degrees).
- The angle of the elbow's flexo-extension obtained from the video record with Kinovea v. 0.9.5 (Degrees).

Acquisition procedure:

1. Both IMUs where putted into the subject's arm.
2. The 0x69 IMU was in the arm while the other one was on the forearm.
3. The subject was asked for stand while making the maximum extension of the elbow.
4. Then after the calibration was made, the subject was asked to follow the metronome rhythm with the arm flexo-extension.
5. The movement was done for 30 seconds.
6. Then after this and while saving the data, the subject rest waiting for the retest which was done with the same procedure.

The data analysis that was performed to make the validation, was a comparison between the signal obtained with the EG, and the signal obtained with the two-dimensional analysis of the video record which was extracted with the validated software Kinovea [18]. From all the samples acquired, a total of N=15 was selected to perform the validity. The statistical variables that were computed are the distance between the pic on the EG signal and the pic on the Kinovea signal. The second variable measures are the RMSE. Both measurements were normalized and after that, the mean and the standard deviation between all of them was made.

VH study

The last study was the VH one, the main difficulties of it was to make a tri-dimensional joint (ankle) measurement, with one sensor on a vertical position and the other one horizontally, also all the noise added to the accelerometer because of the movement on the gait itself was another step in the complexity. Also, a secondary objective of this study was to have a control group for the comparison with the arthrodesis patients.
At this phase of the prototype, it was fully wearable, the microcontroller was in its container and the batteries were connected. The controller box was fixed on the upper side of the knee, and while one sensor was on the leg the other one was on the instep as can be seen in Figure 29.

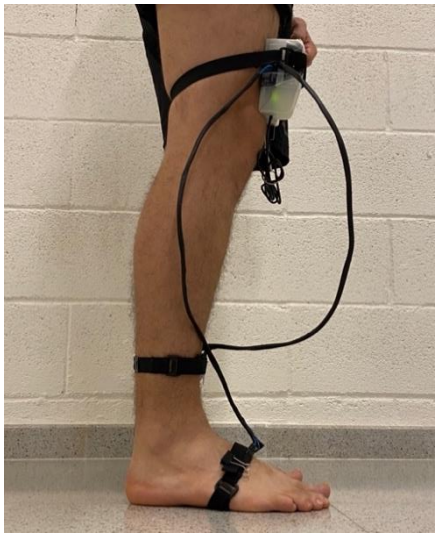

Figure 3. Ankle's set up with one MPU fixed on the toe and the other one on the leg. The microcontroller and the battery is on the distal anterolateral thigh.

As mentioned above, this study was divided on two different groups, the healthy group and the arthrodesis group, the first one was composed by 15 healthy people while the second one had 7 patients. The test in both cases consisted of a round-trip corridor.

Variables measured:

- Flexo-extension range of movement of the ankle's joint (Degrees).

Acquisition procedure:

1. The final prototype was set up on the selected leg.
2. The controller was fixed on distal anterolateral thigh.
3. Both MPUs were facing their wires to the same direction.
4. The subject was asked to walk from along walkway twice with the EG.
5. When arriving to the opposite wall, the subject was asked to stay without turning because it is not a target, and it would add unnecessary noise to the samples.

Results:

HH study

The main results obtained on the goniometry test were useful to calibrate and improve the acquisition software. All the signals can be seen at Figure 30.

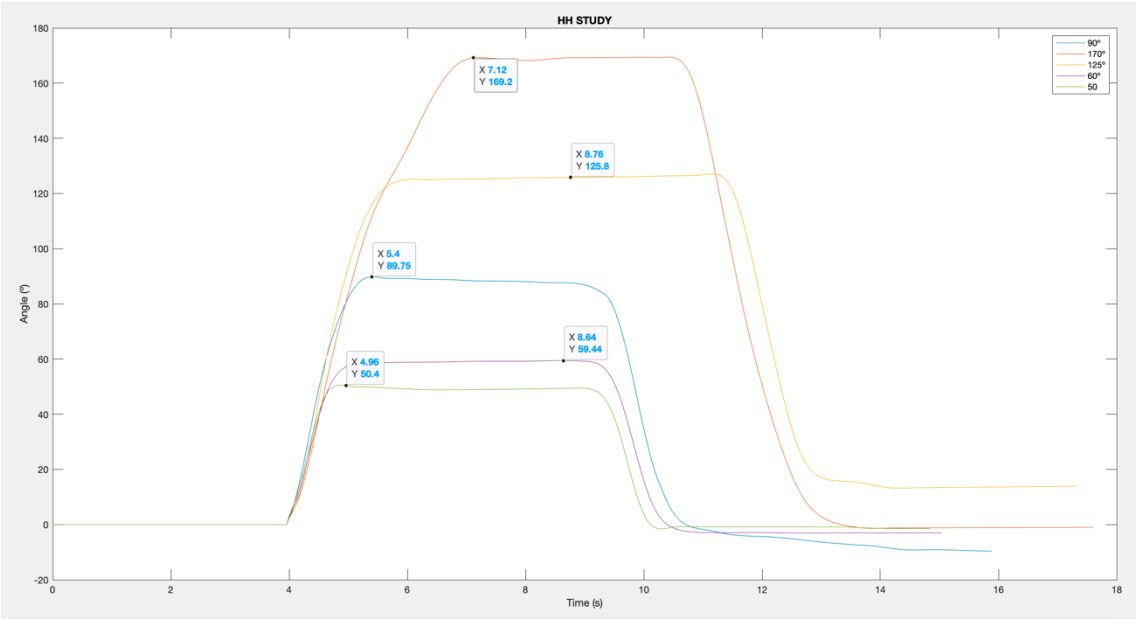

Figure 4. Some results of the HH study, plotted with a MATLAB code.

The movement presented on the Figure 30, refers to some inclination angles that were computed. This figure is only a selection and extraction of 5 signals that clarify the results obtained, as said, the rest of the signals can be check on Annex 3.

VV study: Validity

The results obtained with the VV study were plotted with a MATLAB code (Annex 7) and can be checked on Figure 31.

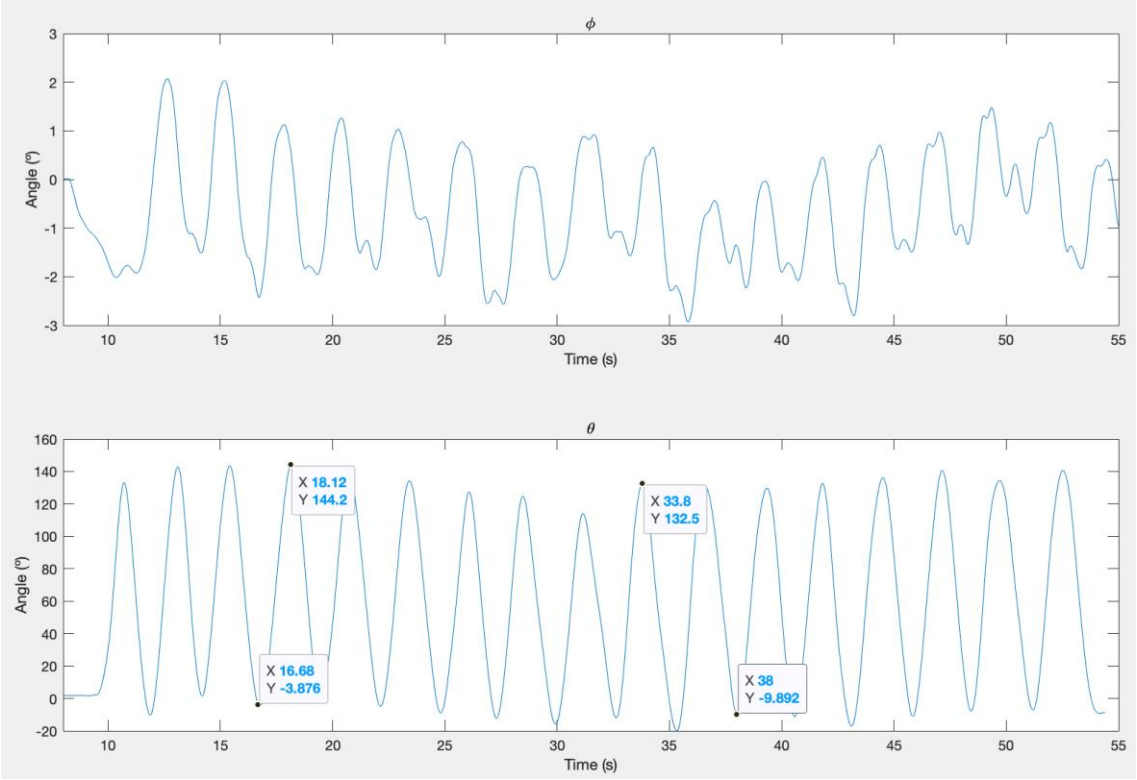

Figure 5. Movement with the elbow criteria. The top graph refers to the varus-valgus natural movement, while the second graph represents the flexo extension movement.

As figure 31 shows, there are multiple flexo-extension movements, those goes from 0º to 145º in normal and healthy movements, some negative values might appear on hiper-extensives elbow. The axis to be analyzed to extract the flexo-extension movement is the θ axis.

Another feature that can be extracted with the prototype is the varus-valgus movement (the ϕ axis). This movement is quite more complex to validate with the video record, so it is validated only with qualitative criterions.

The rest of the results of this study were used on the validation process and can be found on Annex 4.

There was a total of N = 28 samples from which 17 were considered as valid, some exclusion criteria were considered for some signals in which for example the set-up of the device was not rigorous, the output data had some human problems or mostly, the video-record was not valid for the two-dimensional analysis. From the total of N valid samples, 15 were extracted to perform the validity test and the statistical analysis.

Figure 32 is an extract from an evaluation during the validation process, it can be checked the similarities between the EG signal and the Kinovea's signal.

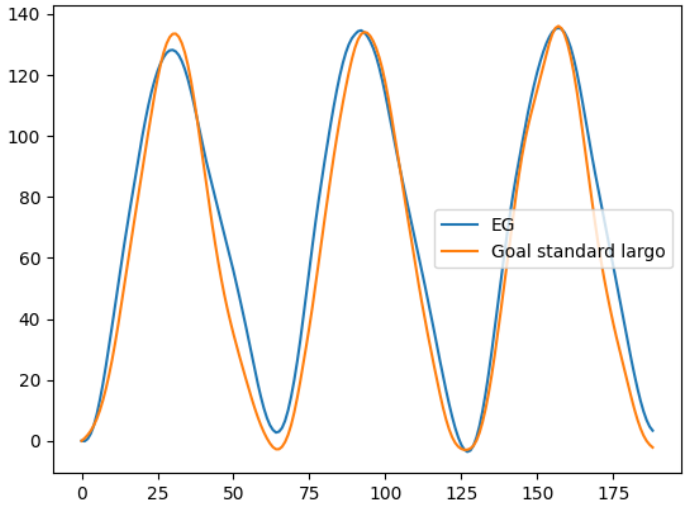

Figure 6. Comparison between the EG signal obtained (blue line) with the Kinovea signal (orange line).

The total results of the validation can be checked on Table 3 and on a more detailed version on Table 4.

Table 3. Summary table of the results, with the mean and the standard deviation of all the 15 measurements.

N samples	Peak error (º)	Peak error (%)	RMSE	Normalized RMSE (%)
15	2.86 ± 1.99	1.97 ± 1.37	14.56 ± 6.30	4.08 ± 1.76

Table 4. Full table of the 15 samples with the measures made with a python code.

ID	Peak error (º)	Peak error (%)	RMSE	Normalized RMSE (%)
15	3.57	2.46	6.80	1.88
16	1.33	0.91	14.94	4.15
17	1.40	0.96	10.20	2.83
18	3.25	2.24	12.50	3.40
20	0.60	0.41	10.46	2.90
21	0.22	0.15	14.11	3.90
25	3.80	2.62	25.8	7.10
28	1.29	0.88	7.65	2.10
29	1.40	0.96	17.25	4.70

33	5.40	3.72	13.90	3.80
34	2.67	1.84	8.85	2.40
36	1.70	1.17	17.22	4.70
37	3.60	2.48	29.86	8.20
38	6.70	4.62	17.60	4.90
40	6.02	4.15	13.80	3.38

VH study:

As said on methodology, the aim of this study is to get in touch with one of the most complex joints to measure on the body, not only because of the combination of both methods of computing angles, but because of the linear acceleration added to the system because of gait, heel strike… The results of the healthy subjects can be checked on Figure 33 and figure 34. The rest of the acquisitions are on Annex 5.

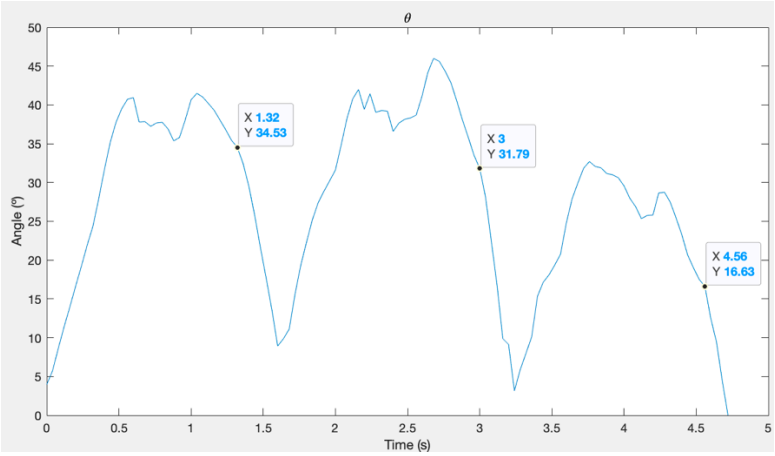

Figure 7. It represents the Flexo-extension ankle during a full walkway of one subject.

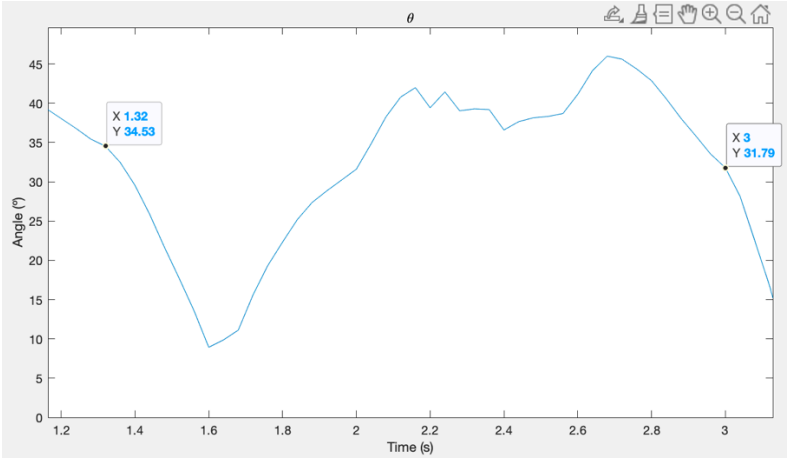

Figure 8. Full gait cycle, the cycle goes from heel strike to heel strike. Those events are the ones marked.

It can be checked that as seen on VV study, the θ refers to the flexo-extension. The other sub-study within this final challenge was to take this project to a clinical case study, where the previously measured ankle group would be the control group and the clinical group are arthrodesis patients. The result of this study can be checked on figure 35 and figure 36. To identify the ankle range of motion from a complete gait cycle and provide a clear comparison between normal gait and the pathological gait. The rest of the samples are on Annex 6.

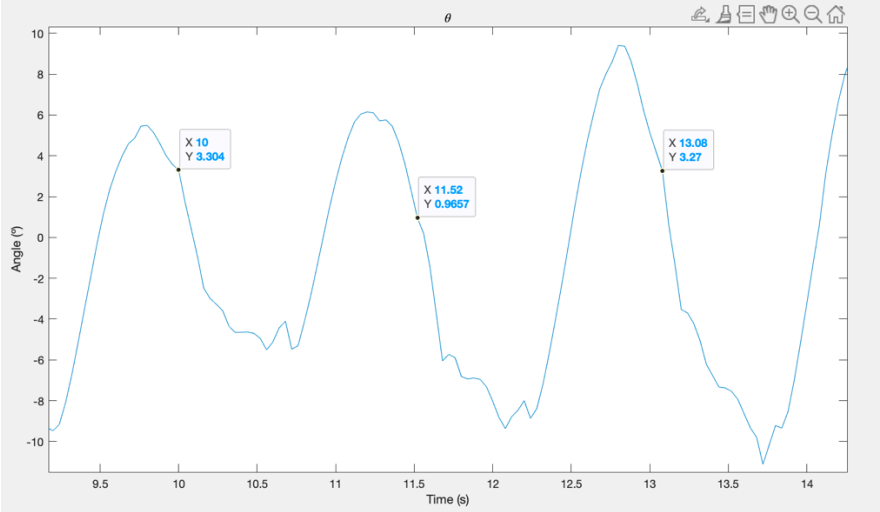

Figure 9. Arthrodesis patient's walkway.

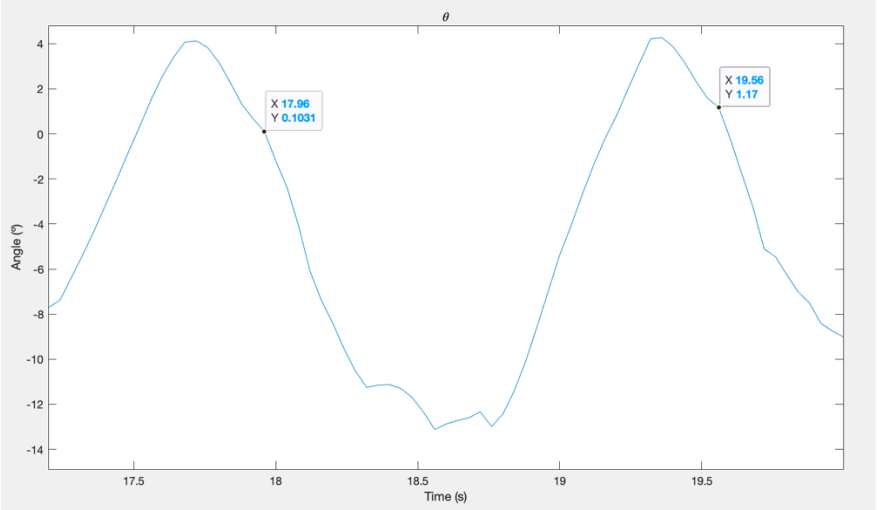

Figure 10. Individual gait cycle from an arthrodesis patient

On figure 35, there is a full walkway with the different gait cycles of the arthrodesis patients while on the other one (See figure 36) it is only an individual complete gait cycle from one heel strike to the consecutive one.

Discussions

Main results

HH Study:

The main results on the HH study, meets the objectives sets as the inclination angle is obtained correctly for finally obtaining the desired joint angle on a horizontal plane. No statistical analysis was made here because of the observative aim.

VV Study:

Some features can be extracted from the signal, the morphology of the signal is a sinusoidal one, this make sense as the movement is repetitive, strictly it cannot be considered a periodical one because the subject did not make the same movement on each repetition. Also, we can know the maximum flexion of the arm by seeing the maximum peaks of the signal. Moreover, the minimum peaks are the maximum extension of the elbow.

The statistical results that the VV study shows are quite ambitious. Almost all the signals had the expected results.

The variables measured to quantify the error of the signal compared with the validated system Kinovea, were the distance to the main peak, as the amplitude is the main application of the goniometry for computing the range of movement (ROM). And the RMSE value to check how both signals fit between them.

As it has been widely explained, the ROM for the flexo-extension of the elbow is 0º-145º, and the amplitude error obtained on the system is $\pm 2.86º \pm 1.99º$ (mean $\pm$ SD). Which can be normalized as an error of $\pm 1.97\% \pm 1.37\%$ (mean $\pm$ SD).

The other statistical variable computed was the RMSE, which result on a $\pm 4.08\% \pm 1.75\%$ (mean $\pm$ SD).

So, considering the low-cost material that has been used, obtaining a $\pm$2.86 degrees error on the amplitude on average out of $\pm$140º of ROM is more than a satisfactory result. As S. F. Van Rijn published on 2018, the accepted mean error is $\pm$11.5 degrees in standard goniometry [19]. Then, L. Bennet on 2013, found an RMSE of 3.9 degrees while this project has obtained 4.09 normalized degrees [15].

VH study

The results obtained at the VH study are a little bit more abstract and complex to validate with any two-dimensional analysis (video record), so this study analysis like the first one is qualitative. At the result can be checked that the ROM of the healthy group (figure 33). Is higher than the ROM from the arthrodesis patients, as expected. Also, the different cycles of the gait could be appreciated on the signal.
It has been identified the heel strike on both signals, this feature can be used to separate a full round-trip corridor into different cycles of the gait.

Limitations

Some projects boundaries that were found during the research and development of the project were:

1. Another limitation is that there is a need for two wires that goes from the controller box to each sensor. With more budged the system could be fully wireless.
2. It is also an obvious limitation that the price of the sensors limits the accuracy of the measurements.
3. The BLE communication limits the rate of the samples to 1/25 samples/seg.

Future research

The future developments that could be done are:

1. To try to solve the previous mentioned boundaries.
2. The portability and scalability of the project makes it suit perfectly for working in future lines with mobile phones or other wearables.
3. To increase the DOF of the sensor as the MPU6050 that was used had only 6 DOF instead of 9. Having nine degrees would imply that the sensor would have a magnetometer. One example of this 9 DOF device is the MPU9050. This ampliation would have allowed measuring rotation movements. This discovery

took place later, while the final development, so it was too late to change the sensor.

4. To test the prototype as a clinometer or a goniometer for spine and fingers.
5. To test the system on unusual situations such as HV study.

Personal approach

For me, this project has been a full new challenge as the development has showed me the full innovation path, from getting the first idea, to prove if it is really feasible, then discovering how to connect all the hardware and finally developing the code and most of the time, solving bugs and errors… But the result is amazing, and it is better than my initial expectations were.

Also, the experience of creating something and seeing it on the final stage on patients' body, talking to them and seeing their aim to help the evolution of science and their willing to maybe get better treatments for their pathology… It was the most rewarding of all the project and the degree…

Now the project has been complete, and I am looking forward to news ideas and developments on the field, but always having in mind this project as my first one.

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