

Development of technique for measuring muscle activity and knee motion in children with CP

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Contents

1. Abstract	4
2. Sammanfattning	5
3. Acknowledgements	6
4. Acronyms	7
5. Introduction	8
6. Background	9
6.1 About CP	9
6.1.1 Diagnosis and Clinical features	9
6.1.2 Symptoms	10
6.1.3 Causes	11
6.1.4 Treatments	11
6.1.5 CPUP	11
6.2 The knee joints	12
6.2.1 Bones around the knee joint	13
6.2.2 Muscles around the knee joint	13
6.3 EMG signal in children with cerebral palsy	17
7. Methods	18
7.1 Inertial measurement unit (IMU)	18
7.2 Analog to digital Converter (ADC)	19
7.3 Implementing the Teensy board	22
7.4 Implementing the sensors BNO080	23
7.5 Implementing the sensor ADS1299	26
8. Results and discussion	28
8.1 The testing phase with BNO080	28
8.2 Human measurements with BNO080	29
8.3 Human measurements with BNO080 and ADS1299	34
9. Future work and developments	39

10.	Conclusion	40
11.	Appendix	41
12.	References	46

1. Abstract

Cerebral Palsy (CP) has an impact on muscles and movement. This happens due to brain damage before the age of two years. Either sometimes before birth, during childbirth or after birth. According to hjarnfonden.se, 200 children are added annually in Sweden with CP.

People living with CP have these weaknesses for the rest of their lives. CP is not progressive disorder, that means brain damage can't be repaired but at the same time, it cannot get worse.

There are many different motor symptoms, but weakness and reduced muscle control are present in everyone and leads to delayed motor development in children with CP.

Therefore, early treatment can help children with CP and increase their life quality.

There is no definitive causation for this condition, but scientists are agreed that CP is caused by damage to the brain. This includes physical damage and infection in brain due to reduction of oxygen for some reason and many other causes.

The aim for this project is to develop a method to measure the knee angle and muscle activity around the knee of children with CP during normal daily living for longer time periods. This can help physicians and physiotherapists to do follow-ups, and in the long run, find better treatments for these children.

2. Sammanfattning

Cerebral Pares, förkortat CP, är en funktionsnedsättning som påverkar muskler och rörelse hos den det drabbar. Funktionsnedsättningen orsakas hjärnskador före två års ålder, antingen före födseln, under förlossningen eller efter födseln.

Barnen som lever med cerebral pares har dessa svagheter under resten av sitt liv. CP är inte en progressiv störning, d.v.s. hjärnskadorna kan inte läkas men samtidigt blir inte skadorna värre.

Det finns många olika motoriska symtom för personer med CP, men svaghet och minskad muskelkontroll finns i alla symtomen och leder till försenad motorisk utveckling hos barn med CP. Därför kan tidig behandling hjälpa barn med CP att få en bättre livskvalitet. Enligt hjärnfonden.se tillkommer det 200 barn årligen i Sverige med CP. Studier har visat att CP orsakas av någon typ av hjärnskada. Det kan t.ex. vara en fysisk hjärnskada, en infektion i hjärnan eller skador som uppkommit pga. syrebrist i hjärnan.

Det finns ingen direkt samband för denna funktionsnedsättningen, men studier har visat att CP kan orsakades av en hjärnskada och har symtomen fysisk skada och infektion i hjärnan på grund av minskad syre av någon anledning och många andra orsaker.

Målet för examensarbetet är att utveckla metoder för att mäta knävinkeln samt EMG-signaler från muskler runt knäet. Inspelning av mätvärdena ska vara för en längre period (24 timmar). Sedan sparas värdena i ett minneskort för analysering. Resultaten av analyserna kan hjälpa läkare och fysioterapeuter att hitta bättre behandling för barn med CP.

3. Acknowledgements

First and foremost, I would like to express my gratitude to my supervisor Nebojsa Malesevic who helped me achieve my goals from beginning to the end. I will always be grateful for your wisdom and support. Another person I would like to thank is my assistant supervisor Christian Antfolk who shared his knowledge, helped and supported me throughout this project. I would also like to express my gratitude to Ingrid Svensson, who gave me the opportunity to work on this amazing project.

I would also like to thank the staff at the department of Biomedical Engineering for providing me with coffee and breakfast on Fridays. The Christmas train serving gingerbread cookies was wonderfully.

And lastly, a thank you to my families for their love and support.

4. Acronyms

CP	Cerebral Palsy
CPUP	Cerebral palsy follow-up program
GND	Ground
MCU	Microcontroller
I2C	Inter Integrated Circuit
IMU	Inertial Measurement Unit
DC	Direct Current
AC	Alternating Current
EMG	Electromyography
GMFCS	Gross Motor Function Classification System
LED	Light-emitting diode
IDE	Integrated development environment
RMSE	Root mean square error
ADC	Analog digital convertor

5. Introduction

Cerebral palsy (CP) can be caused by different types of brain injuries. This damage can happen before birth, during or after the birth of the child. There are no medicines for CP, but there are treatments and exercises that can relieve the symptoms.

The purpose of this project is to design a device that can record knee angle and EMG signals from the muscles around the knee in children with CP. This device should be adjusted for children with CP and be able to record muscle signals for 24 hours.

There are many studies and research on CP in children. A lot of information for this master thesis project have been found through the home page of the CPUP project, <http://cpup.se/> Here you can find reports from previous research studies, facts about symptoms and descriptions of how it is to live with the condition. In this master thesis project, a lot of information from previous research and education of children with CP have been used. Furthermore, it is essential to know what it is like to live with CP. This can help facilitate working with it.

The aim of this project is to investigate how CP can affect the mobility in the lower limbs. More specific, it is the movement and muscle activity around the knee that are in focus. To achieve such a goal, it is necessary to know which knee muscles are best to use for measurement and how many muscles that should be included in the test. Finally, a method should be developed to record and analyze the values from the EMG unit.

The project is a continuation of "Developing a prototype using IMUs to do 24 hours measurement of knee joint mobility in children with Cerebral Palsy" a master thesis project from 2019 [7], where the angle of the knee was measured. The prototype measuring knee joint motion has here been improved and, as a further extension of that project, here EMG measurement from relevant muscles were added. The result from this project can be useful to a physician to compare which muscles are active for a child with CP and a child without CP, for the same movement in their knee. This means that physicians can obtain information that they can use to determine how to design better treatment for the children with CP.

6. Background

The following chapters give an overview of cerebral palsy, sensors, and software to be used to achieve the goal of this thesis. It will also include a summary of other studies and research about children with CP.

6.1 About CP

Cerebral Palsy results from a brain injury and has an impact on muscles and mobility and can occur due to brain damage before the age of two years. This damage can occur before birth, during or after the birth of the children. There are no medicines for CP, but there are treatments and exercises that can relieve the symptoms. Aisen et al [3] defined CP as a "motor impairment that limits the activity and is often accompanied by impaired cognition, communication, and sensory perception, behavioral abnormalities, seizure disorders or these features combined".

There are many different motor symptoms, but weakness and reduced muscle control are present in everyone and lead to delayed motor development in children with cerebral palsy. Children with cerebral palsy have these weaknesses for the rest of their lives.

6.1.1 Diagnosis and Clinical features

The typical initial characteristics of the diagnosis of cerebral palsy are slow motor development, abnormal muscle tone, and unusual posture. Tests are performed to eliminate progressive hereditary neurologic or metabolic disorders causing the observed abnormalities (Figure 1). These tests did considering the clinical picture, pattern of development of symptoms, family history, and the factors that may affect specific diagnoses [2].

CP is not a progressive disorder, which means brain damage can't be repaired, but at the same time, it cannot get worse.

The tests are based on the clinical picture, the image of the development of symptoms, family history, and other factors influencing the probability of specific diagnoses. MRI or computed tomography examination shows more precisely what has been damaged in the brain [1] [2].

TABLE 1
Differential Diagnosis of Cerebral Palsy

<i>Diagnosis</i>	<i>Features</i>	<i>Diagnostic test</i>
Arginase deficiency	No neonatal onset; progressive spastic diplegia; subsequent dementia	Measurement of serum amino acids shows a dramatic increase in arginine concentrations; ammonia levels elevated (range: 85 to 170 mcg per dL [50 to 100 μmol per L])
Glutaric aciduria type 1	Progressive dystonia; choreoathetosis; progressive movement disorder developing during the first one to two years	Serum or urine test for the presence of glutaric acid
Juvenile neuronal ceroid-lipofuscinosis (i.e., Vogt-Spielmeier disease)	Onset after five years of age; progressive loss of cognitive abilities; progressive extrapyramidal symptoms (e.g., rigidity, seizure, visual failure)	Characteristic inclusion bodies in skin fibroblasts or blood lymphocytes
Juvenile variant of metachromatic leukodystrophy	Decline in school performance; slowly progressive paraparesis	Lysosomal enzyme aryl sulfatase
Lesch-Nyhan syndrome	X-linked disorder of purine metabolism; choreoathetosis; self-mutilation; uric acid or orange crystals in the urine; mental retardation (IQ lower than 60)	Assay for the enzyme hypoxanthine-guanine phosphoribosyltransferase
Mitochondrial disorders	Ataxia; neuropathy; retinitis pigmentosa	Point mutation of mitochondrial DNA at the 8993 location
Niemann-Pick disease type C	Autosomal recessive disorder of intracellular processing of cholesterol; 70 percent have late childhood or adolescent onset; loss of vertical eye movements; choreoathetosis; dystonia; tremors	Demonstration of impaired cholesterol esterification on skin fibroblasts; the gene is on chromosome 18
Pelizaeus-Merzbacher disease	Leukodystrophy classification; mixed pyramidal and extrapyramidal symptoms; X-linked; slow rate of progression; pendular nystagmus; choreoathetosis; microcephaly; spastic quadriparesis	Deficiency of proteolipid protein (a primary myelin protein)
Rett syndrome	Primarily in girls; autistic features; choreoathetosis; progressive spasticity; characteristic loss of purposeful hand function resulting in continuous hand wringing; slow progression	Clinical diagnosis

Adapted from Bass N. Cerebral palsy and neurodegenerative disease. Curr Opin Pediatr 1999;11:504.

Figure 1: Differential Diagnosis of Cerebral Palsy [2]

6.1.2 Symptoms

There are different types of symptoms between individuals with cerebral palsy, depending on which part of the brain that is injured. By "Spastic type" of cerebral palsy, which is the most common type of CP, some muscles are always tense and cannot relax. But other types of cerebral palsy are characterized by involuntary movements in the whole body or

imbalance and disorder in actions. There are other symptoms in CP affecting, for example, skeleton, stomach, intestines or breath [1].

6.1.3 Causes

Sometimes it is difficult to know what is the precise cause of cerebral palsy. In general terms, the disorder is caused by an injury that had occurred in the brain before it was fully developed. The brain is immature before two years of age and the symptoms differ depending on when the brain injury happens and how severe it is [1].

6.1.4 Treatments

There are many different types of treatment to patients with cerebral palsy, it ranges from physical therapy, medication and surgery and which to be prescribed depends on symptoms [2].

In response to increasing evidence for neuroplasticity the focus of rehabilitation treatment has changed from medication to neurological rehabilitation. This shift improves development and function by capitalizing on the innate capacity of the brain to change and adapt throughout the patient's life [3].

6.1.5 CPUP

CPUP is a follow-up surveillance program for people with cerebral palsy that was started in 1994 in Skåne and Blekinge. The program is a cooperative project between pediatric orthopedics and the child habilitation centers.

The purpose of the project was to prevent the occurrence of painful hip dislocations and severe contractures in children with CP by creating a system to follow all children in a structured setting during a healthy upbringing.

In 2005, CPUP became a national quality register, which after ten years of fulfillment, was able to show that it is possible to prevent hip dislocation and reduce the number of children who develop complicated contracture. In 2011, CPUP was extended to scope also for adults with CP. After 20

years of fulfillment in 2015, a sharp reduction in hip dislocations from 10% to 0.5% was achieved for adults [4].

Purpose of CPUP

- The aim of CPUP is that all children with CP or CP-like symptoms should be identified and offered participation.
- To prevent the occurrence of hip dislocation and severe deformities by means of continuous and standardized surveillance, if necessary, combined with treatment at an early stage and thereby optimize the functional ability and quality-of-life of those with CP.
- To increase knowledge about CP.
- To improve the cooperation between the various professionals involved in care around people with CP [5].

6.2 The knee joints

Three bones meet in the patella: the tibia, the femur and the patella and two major muscle groups control the movements around the knee joint. The two muscle groups are called the quadriceps muscles and the hamstring muscles [6].

The knee joint is the largest joint in the body. At the same time, it is vulnerable as it bears an enormous amount of pressure while providing flexible movement [8].

The following part of this chapter start with description of the bone and muscle structure around the knee joint and how they work together. It then continues with describing how the human is able to move the lower leg in different directions.

6.2.1 Bones around the knee joint

The function of the knee joint is to connect the longest bone in the body, which is the Femur (thigh bone) to the Tibia (shin bone). As shown in figure 2, there are two main joints in the knee which work together to form a modified hinge joint that allows the knee to move in different directions. The joint surface located at the top in Figure 2 is the patellofemoral joint where the kneecap (or patella) meets the Femur. The joint surface below the Femur where the Femur meets the Tibia, is called the Tibiafemoral joint [8].

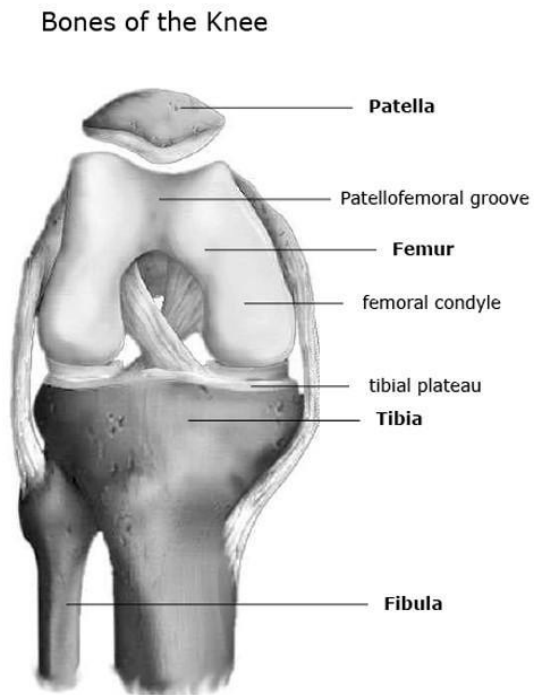


Figure 2: Bones of the knee [8].

6.2.2 Muscles around the knee joint

During a human walk cycle, large parts of the body, such as the arms move by swinging and the core is used to stabilize. The most involved part of the body in a walking cycle are the muscles in the legs around the knee.

The muscles around the knee joint are activated when the human is doing significant movement such as jumping, running, and walking. These muscles work in groups and include the quadriceps, hamstrings, and the muscles of the calf. The figure 3 below shows the muscles in the upper leg and lower leg.

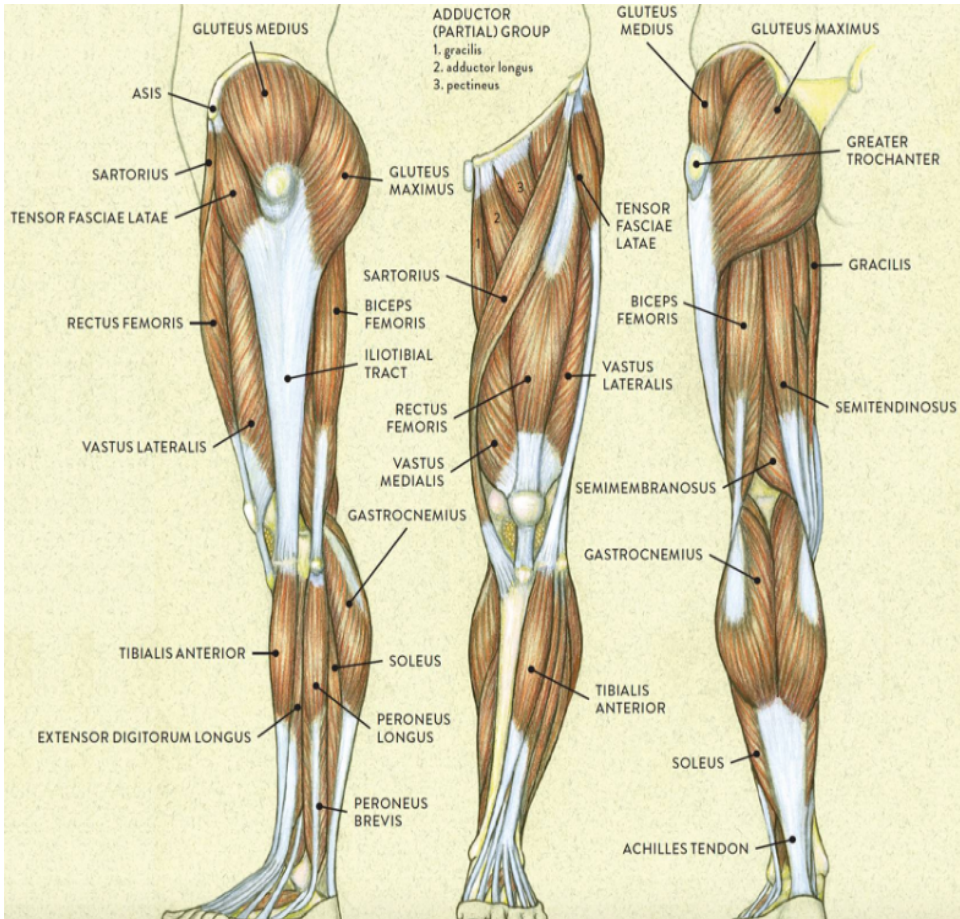


Figure 3: Muscles of the upper and the lower leg [9].

Table 1: Muscles anatomy, muscles around the knee joint upper leg [10].

<p>Quadriceps Femoris (vastus medialis): Origin: Straight head from anterior inferior iliac spine. Reflected head from groove above rim of acetabulum. Insertion: Proximal border of the patella and through the patellar ligament. Function: Extension of the knee joint and flexion of the hip joint.</p>
<p>Quadriceps Femoris (vastus lateralis): Origin: Distal half of the intertrochanteric line, medial lip of line aspera, proximal part of medial supracondylar line, tendons of adductor longus and adductor magnus and medial intermuscular septum. Insertion: Proximal border of the patella and through patellar ligament. Function: Extension of the knee joint.</p>
<p>Biceps Femoris (long head and short head): Origin: Long head: distal part of Sacro tuberos ligament and posterior part of tuberosity. Short head: lateral lip of linea aspera, proximal 2/3 of supracondylar line and lateral intermuscular septum. Insertion: Lateral side of head of fibula, lateral condyle of tibia, deep fascial on lateral side of leg. Function: Flexion and lateral rotation of the knee joint. The long head also extends and assists in lateral rotation of the hip joint.</p>
<p>Semitendinosus: Origin: Tuberosity of ischium by tendon common with long head of biceps femoris. Insertion: Proximal part of medial surface of body of tibia and deep fascia of leg. Function: Flexion and medial rotation of the knee joint. Semitendinosus also extends and assists in medial rotation of the hip joint.</p>

Table 2: Muscles anatomy, muscles around the knee joint lower leg [10].

<p>Tibialis Anterior: Origin: Lateral condyle and proximal 1/2 of lateral surface of tibia, interosseus membrane, deep fascia and lateral intermuscular septum. Insertion: Medial and plantar surface of medial cuneiform bone, base of first metatarsal bone. Function: Dorsiflexion of the ankle joint and assistance in inversion of the foot.</p>
<p>Peroneus Longus: Origin: Lateral condyle of tibia, head and proximal 2/3 of lateral surface of fibula, intermuscular septa, and adjacent deep fascia. Insertion: Lateral side of base of first metatarsal and of medial cuneiform bone. Function: Eversion of the foot and assistance in plantar flexion of the ankle joint.</p>
<p>Soleus: Origin: Posterior surfaces of the head of the fibula and proximal 1/3 of its body, soleal line and middle 1/3 of medial border of tibia and tendinous arch between tibia and fibula. Insertion: With tendon of gastrocnemius into posterior surface of calcaneus. Function: Plantar flexion of the ankle joint.</p>
<p>Gastrocnemius Medialis:Origin: Proximal and posterior part of medial condyle and adjacent part of the femur, capsule of the knee joint. Insertion: Middle part of posterior surface of calcaneus. Function: Flexion of the ankle joint and assist in flexion of the knee joint.</p>
<p>Gastrocnemius Lateralis: Origin: Lateral condyle and posterior surface of femur, capsule of knee joint. Insertion: Middle part of posterior surface of calcaneus. Function: Flexion of the ankle joint and assist in flexion of the knee joint.</p>

6.3 EMG signal in children with cerebral palsy

Some studies can be found in the literature where EMG signals from muscles of children with cerebral palsy have been measured. In one of them, "Quantification of dynamic EMG patterns during gait in children with cerebral palsy" [19] a gait metric for the comparison and quantification of the similarities between patient normative gait-related patterns was developed.

They analyzed three groups of children: two groups with healthy children and one group with the spastic hemiplegic form of CP with different degrees of motor deficits evaluated using the Gross Motor Function Classification System (GMFCS) [19].

In this study, EMG activity from four muscles responsible for different motions in the lower leg was recorded. Vastus Medialis (VM) and Biceps Femoris (BF) were chosen for extension and flexion around the knee and Tibialis Anterior (TA) and Gastrocnemius Medialis (GM) for dorsal/plantar flexion for the foot around the ankle joint.

A part of the study was to process the raw EMG data collected from the four muscles chosen. The processing of the data started with a pre-processing to get rid of all artifacts that often contaminate data from measurements using surface EMG electrodes. Examples of preprocessed data from similar measurements during a gait cycle from another study can be seen in Figure 4.

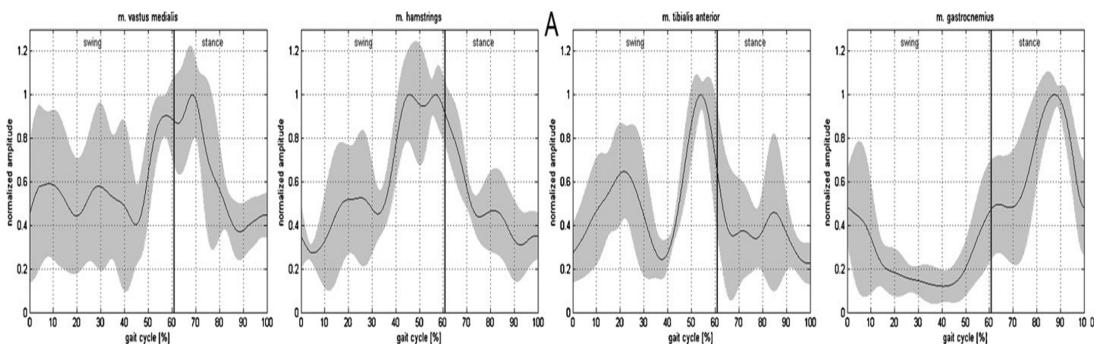


Figure 4: Normative gait related patterns [19].

7. Methods

Measurement of both knee angles and EMG signals from muscles positioned around the knee was the primary goal of this project. IMU sensors were used for measuring the knee angle, and an analog to digital converter was used for EMG signals measurement. Both types of sensors were connected to a Teensy development card. The sensors' characteristics are described in the following section.

7.1 Inertial measurement unit (IMU)

An inertial measurement unit (IMU) can measure position and velocity and other variables by combining the triple-axis gyro, magnetometer, and accelerometer. It is possible to measure motion with high precision in two up to nine degrees of freedom using an IMU. The unit is used in a lot of different equipment such as robotic arms, guided missiles, VR headset or study of human body motion [12], [13].

In the IMU, the accelerometer detects linear acceleration and measures motion in X, Y, and Z direction. The gyroscope measures the angular velocities around three axis. The magnetometer makes it possible to calculate the direction of the sensor by cognizance direction towards the magnetic north [14].

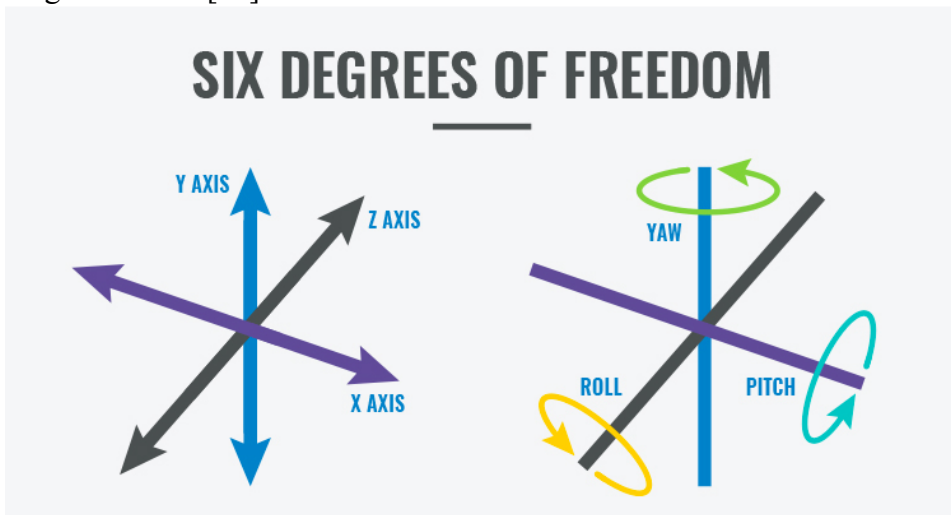


Figure 5: Six degrees of freedom [15].

In an IMU data from all the sensors are combined to give a complete picture of orientation. Acceleration arising from change in velocity or as a consequence of the Earth's gravitational force is measured by the accelerometers. The acceleration can then be integrated once in time to give the velocity and twice to give the distance. A gyroscope is used for measuring twisting or rotational movement as angular velocity of the pitch (x-axis), roll (y-axis), and yaw (z-axis). Further, a magnetometer is used to measure magnetic fields [15]. So the orientation of the sensor relative the gravitational force can be derived the data from the accelerometers can be adjusted. Then the acceleration arising from changes in velocity can be achieved.

7.2 Analog to digital Converter (ADC)

The data given from the sensors of an IMU is in analog format. In order to analyse the data it needs to be converted to digital format. Then an analog to digital converter (ADC) will be useful. The converter is an electronic integrated circuit that receives analog signals and convert them to digital [17].

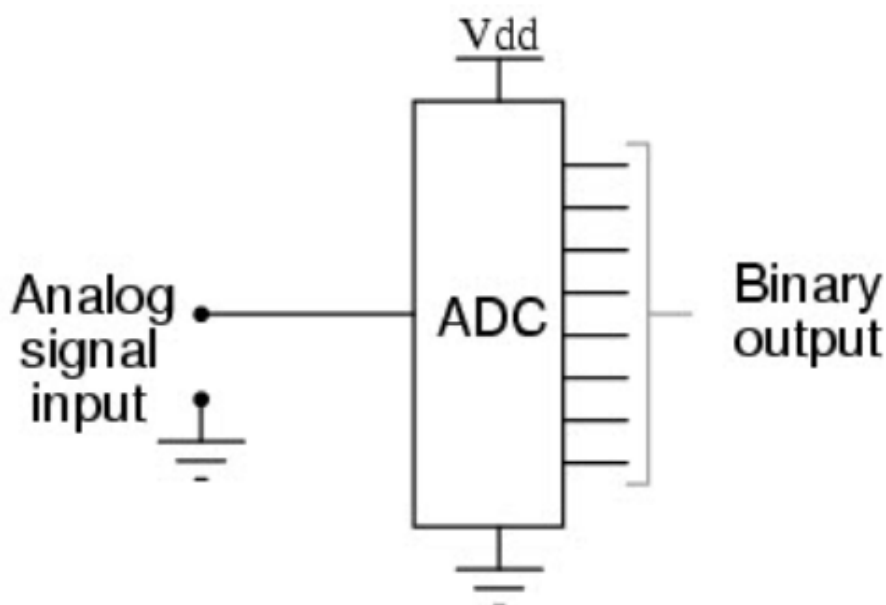


Figure 6: ADC Converter [17].

An ADC measures the ratio of an analog value to a reference value and puts it in the form of digital value. ADC converts any falling or rising edge of the sample clock into a digital signal. That makes by getting the analog signal such as the voltages and then measuring and converting it to a digital signal or binary form consisting of 1 and 0.

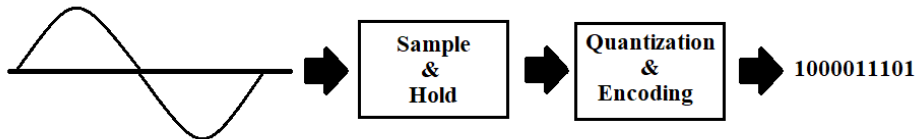


Figure 7: Analog to digital converter.

First, the analog signal is sampled at the special rate, and then the signal quantized in the finite levels. After the quantization, the signal is encoded in the binary format. Quantization level and sampling rate are two factors that determine the accuracy of the digital value.

The figure below shows the conversion of an analog signal to a digital signal. As shown in the figure, ADC 3-bit is used, which means the input signal will get quantized into eight levels ($2^3 = 8$). With 4V inputs, the resolution would be $4/8 = 0,5V$. The quantization error is equal to $\pm\frac{1}{2}$ LSB for 001. This quantization error can be reduced by increasing the number of bits [17].

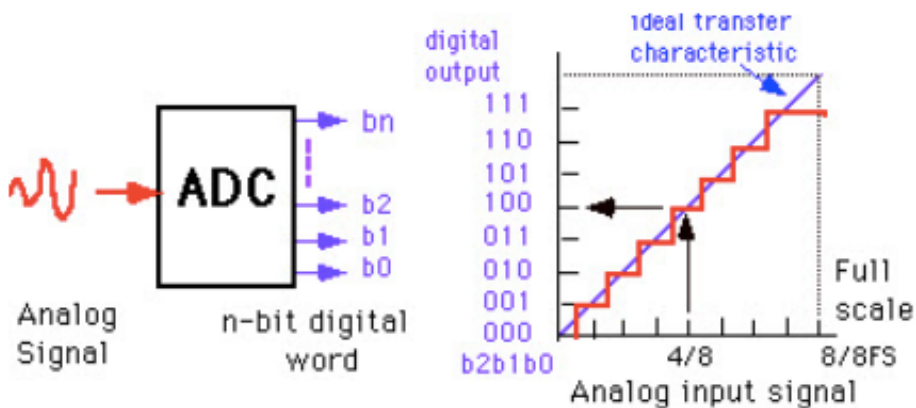


Figure 8: Analog to Digital Conversion Process [17].

The other factor connected to the accuracy of the digital value in the process is sampling. The analog signal is sampled at a particular rate. As it can be seen in the figure 9, the more samples we take over a time period, the more accurately we can represent the analog signal.

According to the Nyquist sampling theorem for a sine wave with a maximum frequency of f_{\max} , the minimum sampling rate should be equal to 2 times f_{\max} . As seems in the figure below, if the sampling rate is less than $2 * f_{\max}$, then the aliasing effect will be seen in the reconstructed waveform, which means the frequency of the constructed signal will be less than the original signal. To avoid this aliasing affect the sampling rate should be at least two times the maximum frequency. So, a low-pass filter is used before converting the signal from analog to digital in order to prevent aliasing.

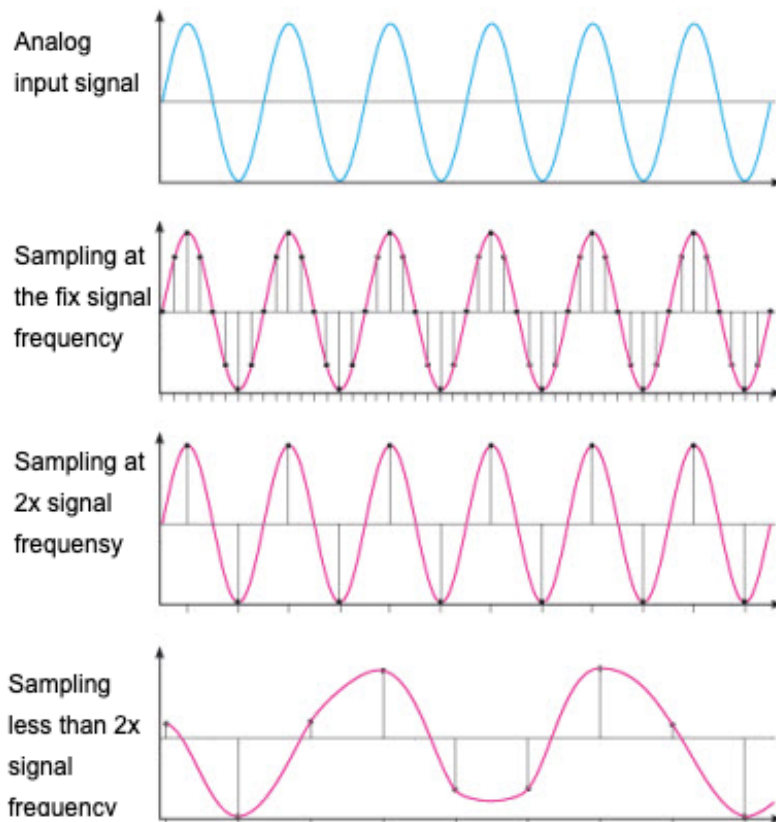


Figure 9: Sampling rate of ADC [17].

In the following of this chapter a step by step description of the development process of how to use the IMU sensors BNO080 and ADS1299 in order to obtain the desired results will be presented.

7.3 Implementing the Teensy board

The Teensy 3.6 board is a tiny package that has many features and a processor by 180 MHZ, 32-bit. The teensy board can use the Arduino Software (IDE) to install the Teensyduino, which allows a user to write programs and upload them on the board. The card has several pins that can be used to connect several other sensors [11].

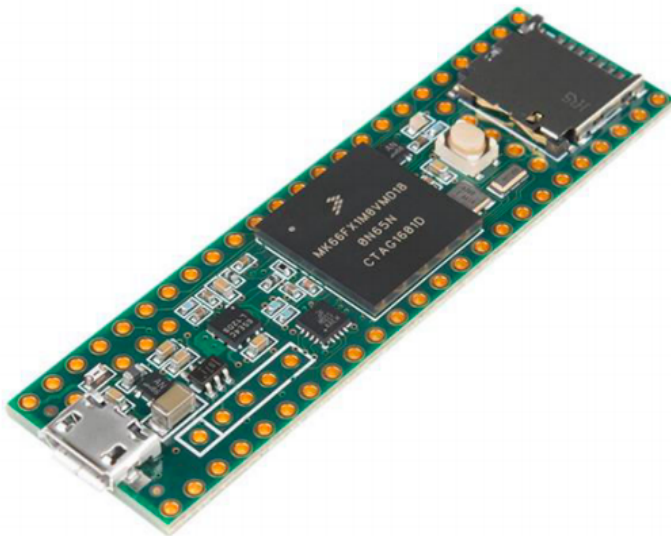


Figure 10: Teensy 3.6 board [11].

Teensy's process also has access to the micro SD card port, which can record data and store in the SD card.

7.4 Implementing the sensors BNO080

The VR IMU has a breakout of three sensors in little chips, as shown in the figure below. The sensors are an accelerometer, a gyroscope, and a magnetometer. All these sensors give 9 degrees of freedom (9-DOF).

IMU BNO080 is a perfect chosen sensor to measure the knee angle since it sense both orientation and motion. The sensor has I2C communication for interfacing with an external microcontroller.

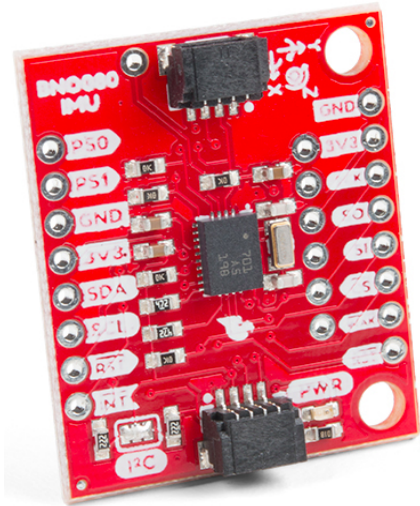


Figure 11: VR IMU Breakout - BNO080 [13].

In the BNO080 are the UART pins broken out as well as a serial-parallel interface that makes it possible to run a higher data rate than I2C use.

Two BNO080 sensors, placed one on the upper limb and one on the lower, have been used to measure the knee angle. ADR jumpers have to be soldered to the two BNO080 sensors to make it possible to connect them to a Teensy board, see figure 12. The addresses of the BNO080 sensors then have to be changed from 0x4B (default) to 0x4A.

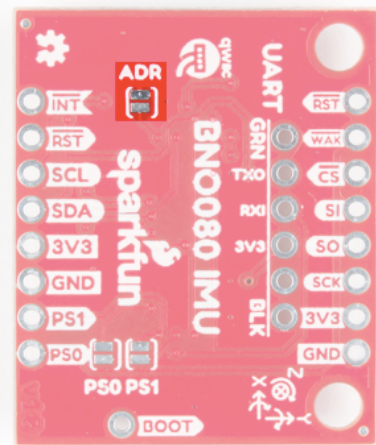


Figure 12: Connecting the I2C ADR jumper [20].

The setup of the Teensy 3.6 and the two BNO080 sensors can be observed in figure 13. This setup was solved by soldering the ADR jumper on the first BNO080 sensor and connecting the I2C channels and Ground to the second BNO080 sensor. Then both sensor channels were connected to Teensy.

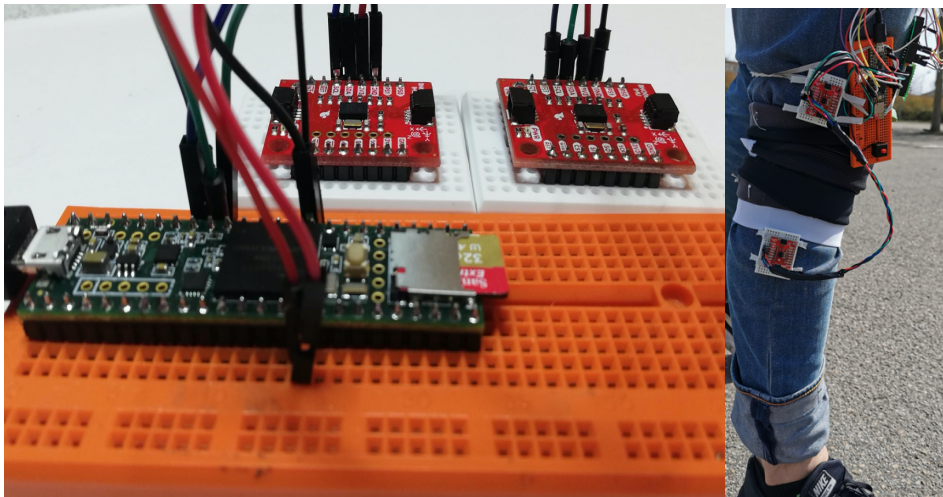


Figure 13: BNO080 and the placement of the sensors on the leg.

The frequency for saved data to the SD card reached 100 Hz, which fitted the desired sample rate.

An example of how the sorted data from the sensors is arranged on the SD card is shown in figure 14. Here the first column correspond to the number of measurements, the second gives the time in milliseconds since Teensy started and the third column gives the knee angle in degrees.

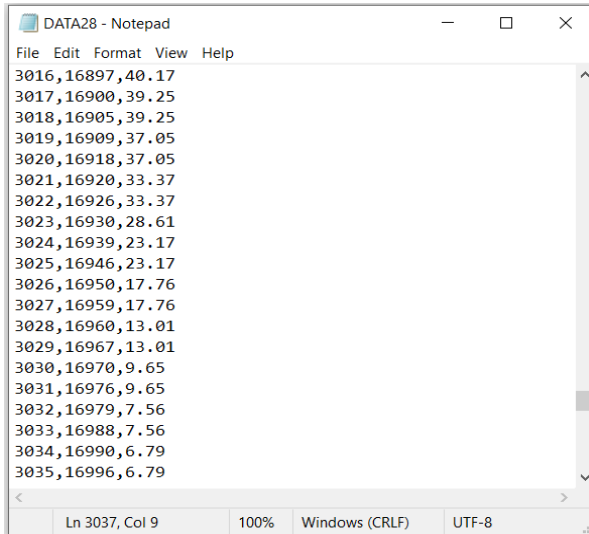


Figure 14: A screenshot of the angle measure text file in 100 Hz.

The data from the SD card is processed in Matlab. A plot of the measured angle as a function of time can be seen in figure 14.

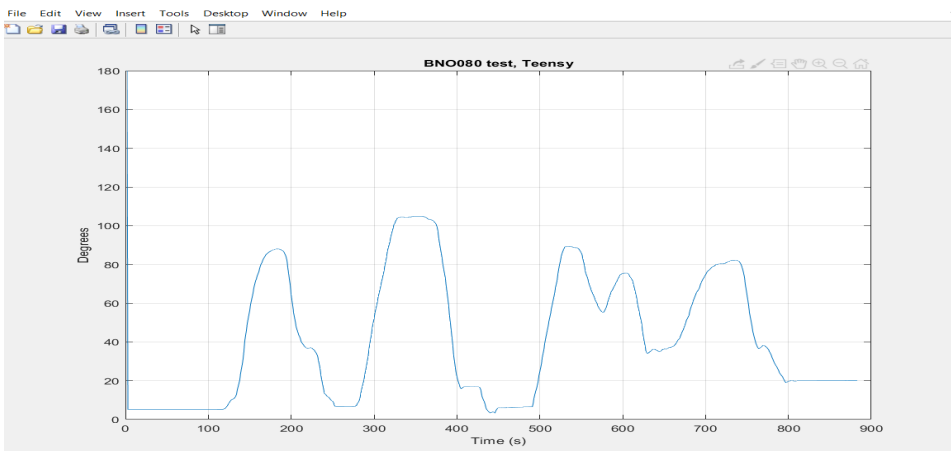


Figure 15: Knee angle data measured by BNO080 and processed in Matlab.

7.5 Implementing the sensor ADS1299

An analog Front-End ADS1299 has been used to develop the EMG recording in this master thesis. The ADS1299 is an 8-channel, low-noise, 24-bit simultaneous-sampling delta-sigma analog to digital convertor (ADC) [16].

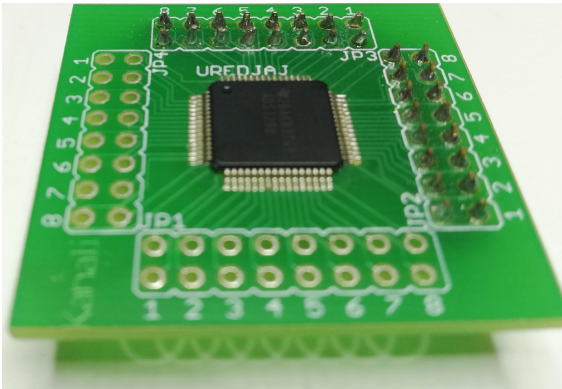


Figure 16: ADS1299, 8-Channel, 24-Bit Analog-to-Digital Converter.

The ADS1299 was designed in a double layer format PBC (Print Circuit Board). The communication protocol between ADS1299 and Teensy is based on SPI (Serial Peripheral Interface).

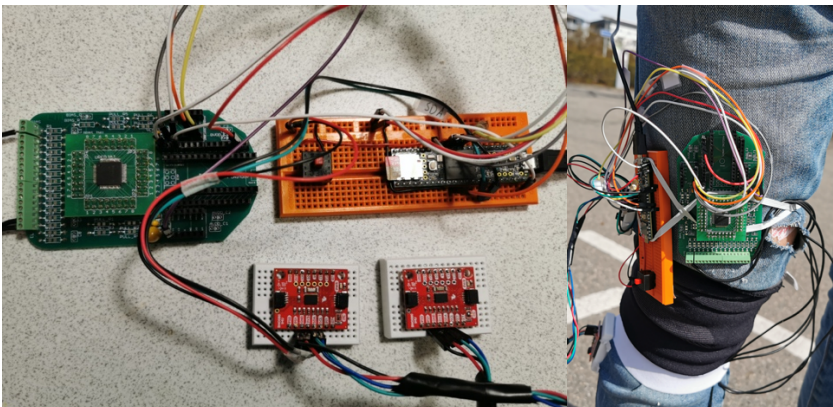


Figure 17: BNO080 and ADS1299 connected to the Teensy and mounted on the test person.

Surface electrodes were attached at one major muscle, Vastus Medialis (VM) in order to test the recording of muscle activity. Vastus Medialis was

chosen since it is big, easily accessible and situated close to the skin, this facilitates the recording. The activity was recorded for a few minutes, as shown in the figure below. The recording is for both knee angle and muscle activity during a walk.

The frequency for saved data to the SD card reached 100 Hz for angle measuring and 500 Hz for EMG measuring.

```

390, 4174, 27.71, 4294949466
391, 4175, 27.71, 4294949503
392, 4176, 27.71, 4294949509
393, 4177, 27.71, 4294949479
394, 4178, 27.71, 4294949491
395, 4179, 27.70, 4294949404
396, 4185, 27.70, 4294949435
397, 4186, 27.70, 4294949424
398, 4188, 27.70, 4294949399
399, 4189, 27.70, 4294949392
400, 4190, 27.76, 4294949423
401, 4195, 27.76, 4294949420
402, 4196, 27.76, 4294949434
403, 4198, 27.76, 4294949417
404, 4200, 27.81, 4294949395
405, 4205, 27.81, 4294949398
406, 4207, 27.81, 4294949403
407, 4208, 27.81, 4294949410
408, 4209, 27.91, 4294949374
409, 4215, 27.91, 4294949377
410, 4216, 27.91, 4294949424
411, 4217, 27.91, 4294949407
412, 4218, 27.91, 4294949399
413, 4219, 27.98, 4294949395

```

Figure 18: Here is the first column correspond to the number of measurements, the second gives the time in milliseconds since Teensy started, the third column gives the knee angle in degrees and the fourth column gives values of EMG measurements in mV.

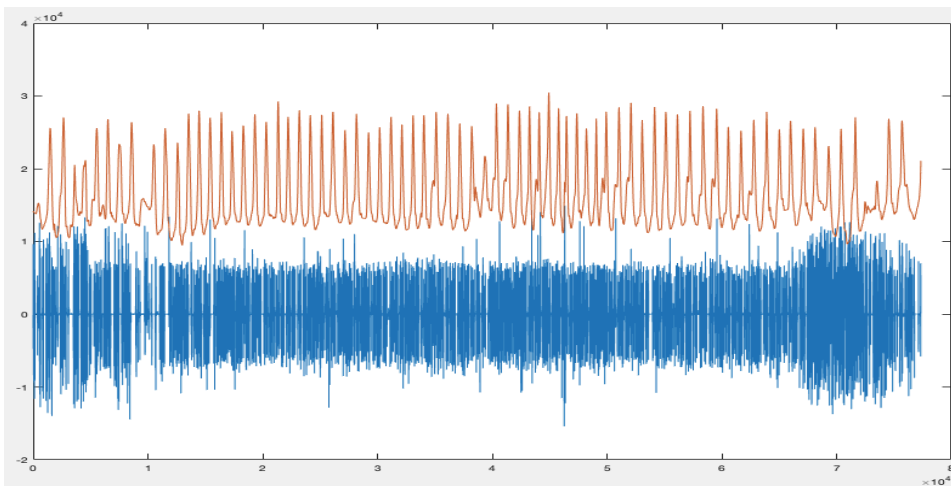


Figure 19: Example of EMG-activity (blue) and knee angle (red) plotted in Matlab.

8. Results and discussion

8.1 The testing phase with BNO080

Two IMUs were attached to a goniometer to check that the angle values given from the sensors were equal to the values read at the goniometer. The trial was used for a shorter period to test the accuracy and get an idea of how the sensors influenced each other. As shown in the figures below, the sensors have been tested for a few different angles.

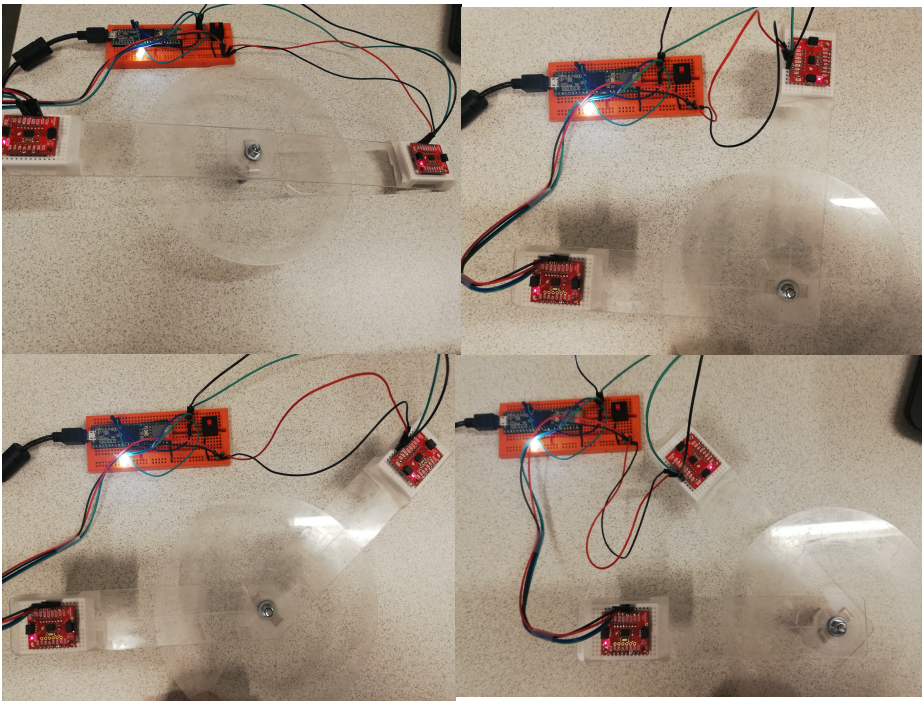


Figure 20: IMU sensors tested in different angles (180, 90, 135 and 45 degrees).

A plot of the measured angle as a function of time can be observed in figure 21.

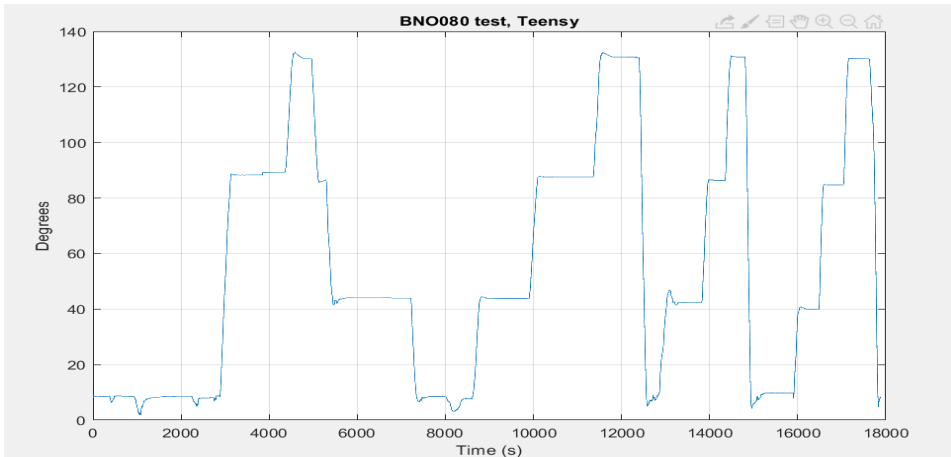


Figure 21: Measured angle between IMU sensors for verification with goniometer.

8.2 Human measurements with BNO080

When the sensors were mounted around the knee of a test person and the measurements started a lot of strange values were obtained. In order to get rid of the errors, the settings of the sensors were changed, and another calibration procedure was chosen. The resulting measurements during walking using some of the different settings are shown in the figures 22-28.

Figure 22 used the "RotationVector" mode, which reports its value of the 3-axis accelerometer, 3-axis gyroscope, and the 3-axis magnetometer.

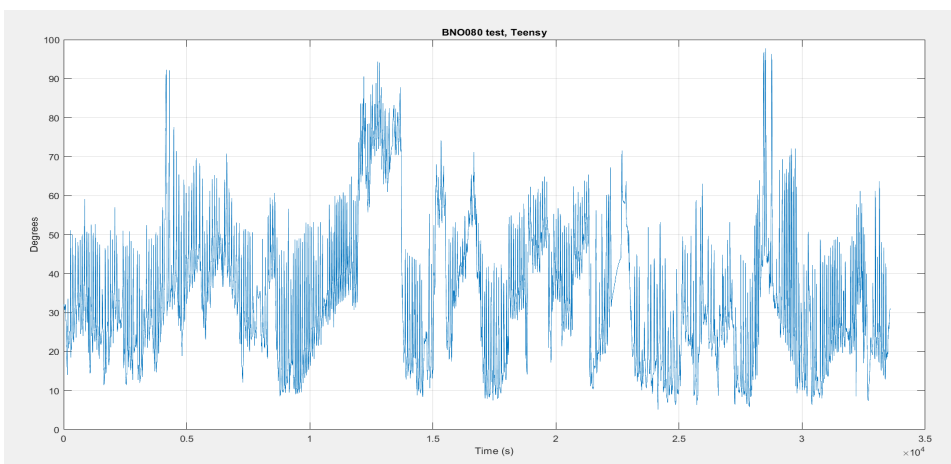


Figure 22: 10 min walking with "RotationVector" mode.

Changing calibration or choosing different mode can cause errors. A plot of the measured angle with the "GameRotationVector" mode can be observed in figure 23, which reports the value of the accelerometer and gyroscope every 10 ms (no magnetometer). When the "GameRotationVector" mode was used the size of the angle was measured better, as shown in the figure below, but it does not calibrate correctly.

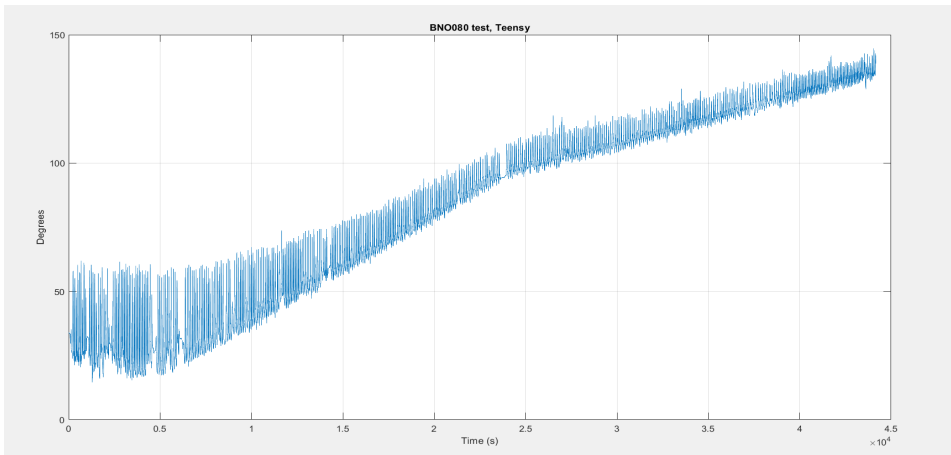


Figure 23: 10 min walking with "GameRotationVector" mode.

The result from using a combination of the "GameRotationVector" and "Magnetometer" modes is shown in figure 24. Here the values of the accelerometer, gyroscope, and magnetometer every 10 ms.

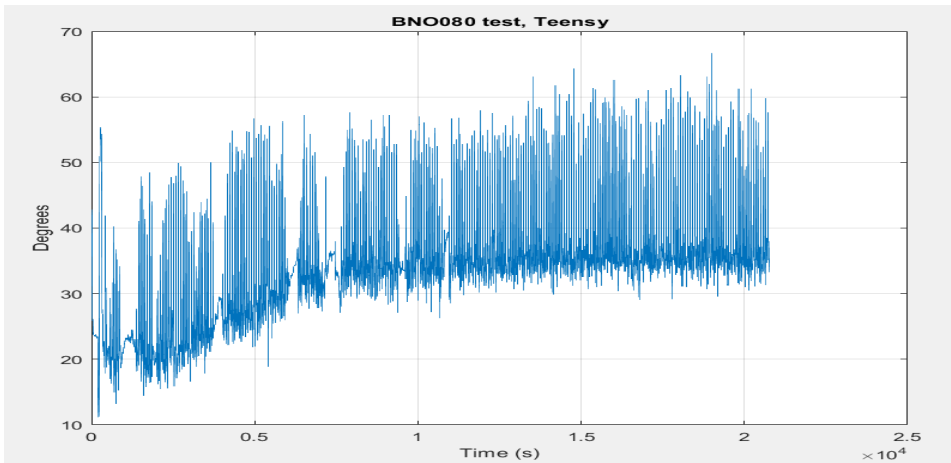


Figure 24: 5 min walking with "GameRotationVector" mode and "Magnetometer" mode.

The result from using all three modes separately during the measurement is shown in figure 25.

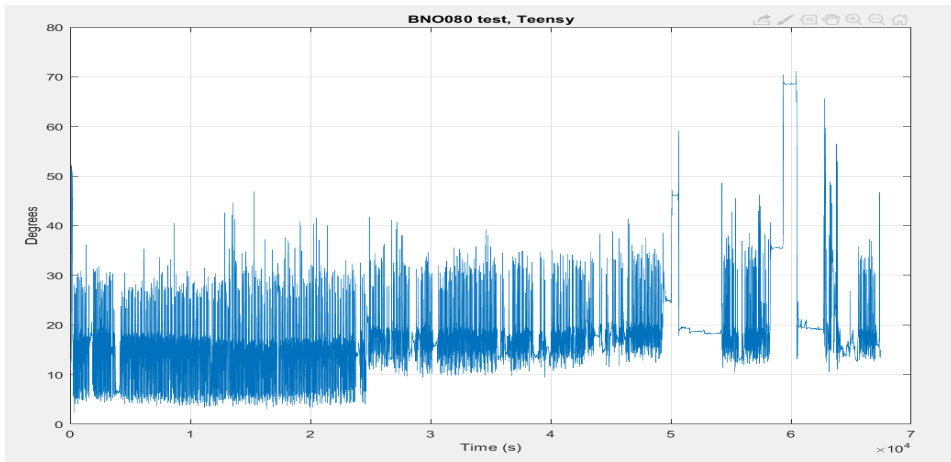


Figure 25: 20 min walking with mode of Accelerometer, Magnetometer, gyroscope.

After a lot of test recordings with IMU sensors and after having compared this with previous tests, I found a much better result by record using the "RotationVector" mode and by calibrating with "calibrateAll()". The sensors used dynamic calibration in the setting. Figure 26 shows a recording of an hour walking. The values measured knee angle seem reasonable when comparing to other studies of walking humans and no drifting was observed.

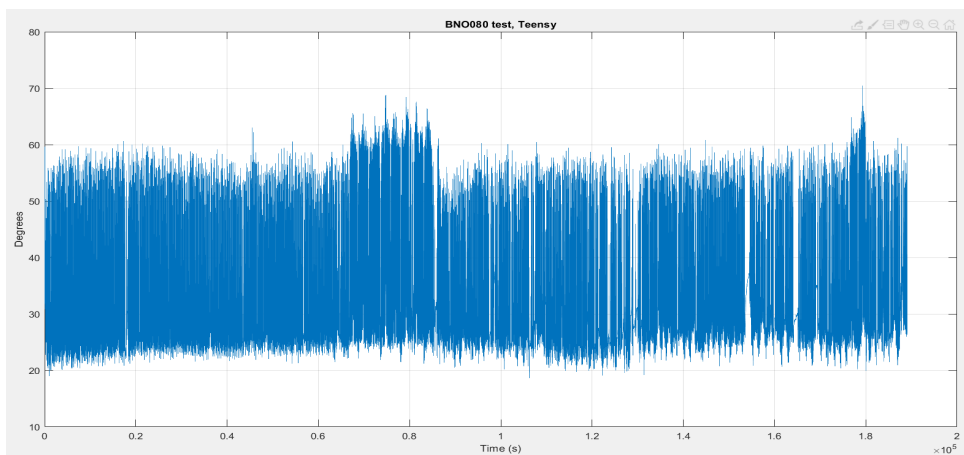


Figure 26: 60 minutes indoor walking using "RotationVector" mode.

In the last tests, the lower frequency of the angle recording is used (50 Hz). Because lower frequency gets a better result and less errors than previous measurements, it should be noted that the saturation is not entirely accurate. Then there are still errors in the measurements.

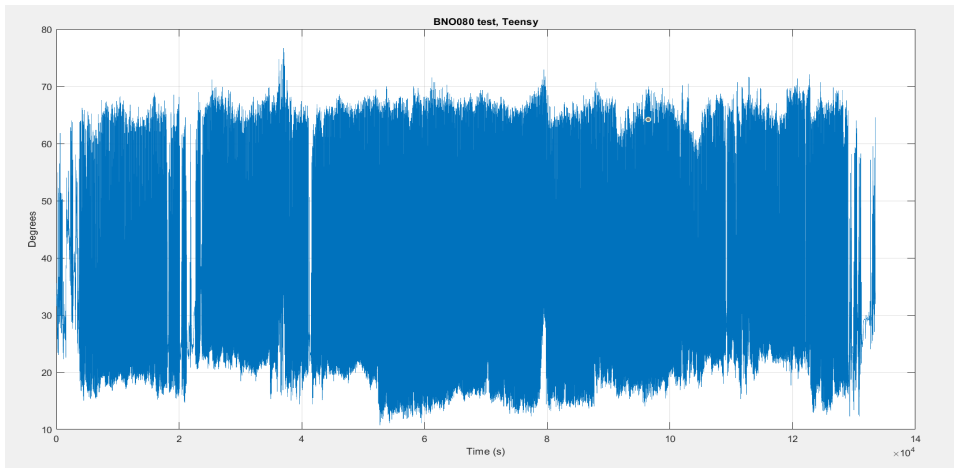


Figure 27: 60 min outdoor walking using "RotationVector".

The result from a 2 hour recording using the settings "RotationVector" mode and "calibrateAll()" is shown in figure 28. This test included activities as walking both indoors and outdoors as well as sitting on a chair. The recording frequency was 50 Hz. As it can be seen in figure 28, much better result from the measurement was obtained but there are still need for improvements.

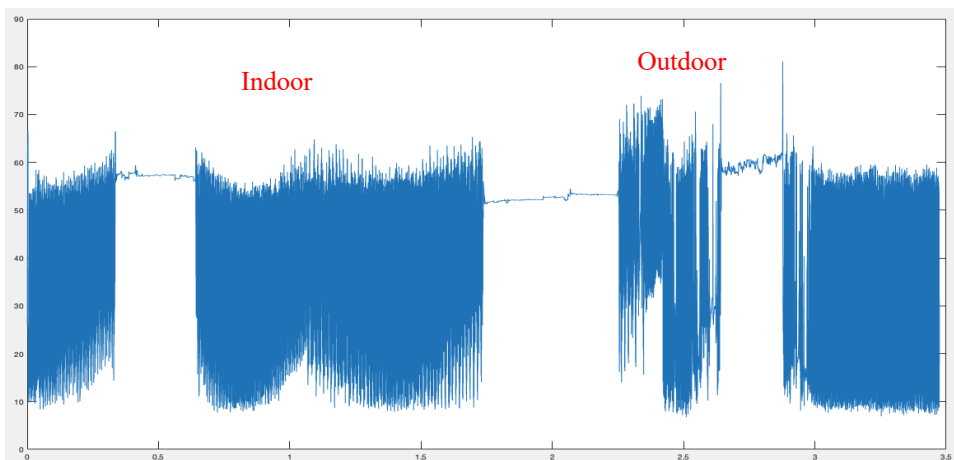


Figure 28: Measured knee angle during outdoor and indoor walking for two hours using the setting "RotationVector".

Measuring with BNO080 sensors shows much less error when measured in the lab room during a short time period such as 10 minutes and using the "RotationVector" mode. But, when the measurements are taken over an extended time period, there are more errors in the measurements and the values of the knee angle is drifting.

Since the BNO080 sensors might be sensitive to external electromagnetic signals or disturbances from surrounding electronics, tests have been done with EMC (electromagnetic compatibility) shielding. The shielding was obtained by wrapping aluminum foil around the IMU sensors. Unfortunately, this did not result in any improvement.

8.3 Human measurements with BNO080 and ADS1299

The next step in the project is developing a procedure for recording EMG signals from some leg muscles around the knee. The muscles chosen are situated at easily accessible locations and are the major ones responsible for flexion and extension in the knee joint.

An example of the measured simultaneous activity from eight leg muscles is shown in figure 29. The electrodes are attached on the skin superficially of each of the individual muscle, in respectively. All eight channels of ADS1299 are used.

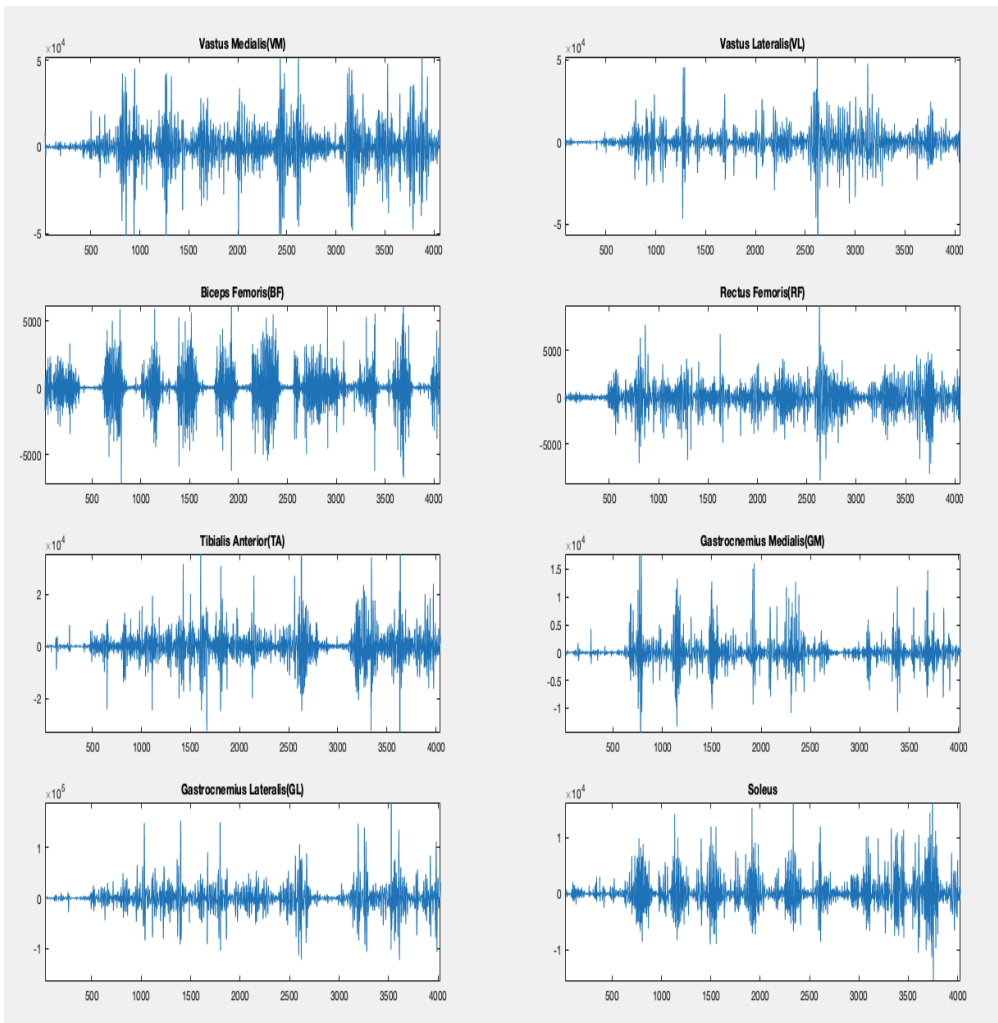


Figure 29: Example of EMG measurements of leg muscles for a time period of 40 seconds.

The EMG recording presented in figure 29 was sampled with 200Hz. The knee angle was simultaneously measured over the same time period using the IMU sensors at 100 Hz. A few minutes recording of knee angle with EMG activity was a good experiment. But when registering for a more extended period, a lot of errors were found in the angle recording.

The figure 30-37 show knee angle and corresponding muscle activity from muscles: Vastus Medialis (VM); Biceps Femoris (BF); Gastrocnemius Medialis (GM); Tibialis Anterior (TA); Vastus Lateralis (VL); Rectus Femoris (RF); Gastrocnemius Lateralis (GL); Soleus. When plotting the EMG signals and knee angle in the same diagram, it is obvious that they are synchronized.

The Rectus Femoris (RF), Vastus Lateralis (VL) and Vastus Medius (VM) crosses the knee via the patella and acts to extend the leg, which means that they are most active when the angle increases. The Biceps Femoris (BF), Gastrocnemius Medialis (GM) and Biceps Femoris (BF) flex the knee and extend the hip, which when reducing angle affects muscles the most.

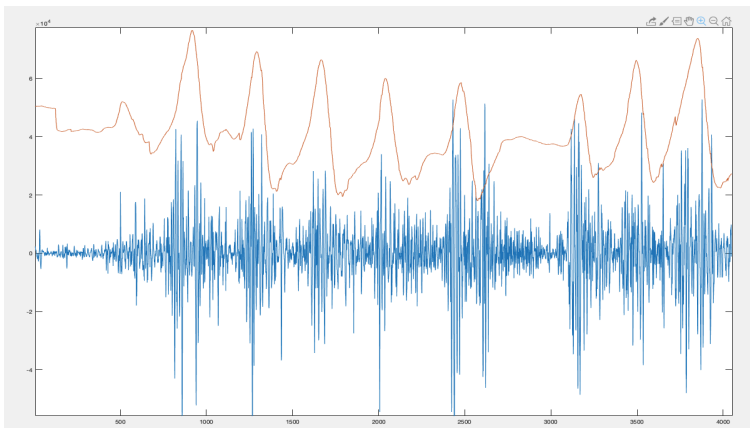


Figure 30: The blue line corresponds to the EMG measurement of Vastus Medialis (VM) and the brown line corresponds to the knee angle.

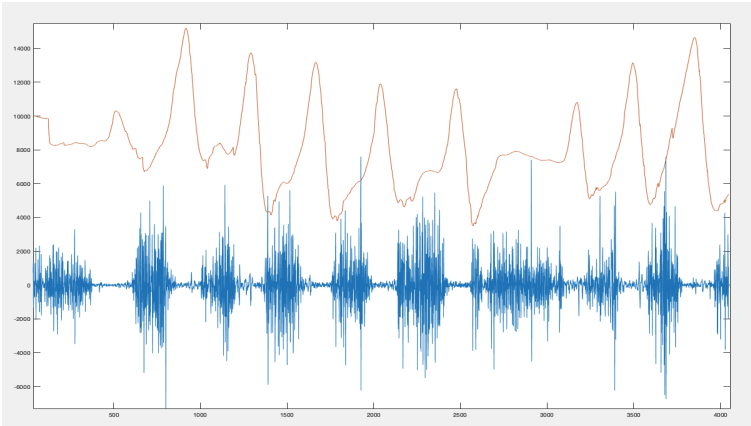


Figure 31: The blue line corresponds to the EMG measurement of Biceps Femoris (BF) and the brown line corresponds to the knee angle.

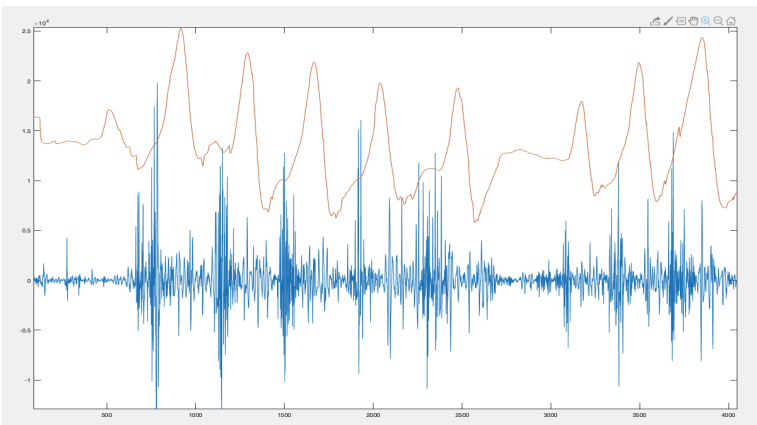


Figure 32: The blue line corresponds to the EMG measurement of Gastrocnemius (GM) and the brown line corresponds to the knee angle.

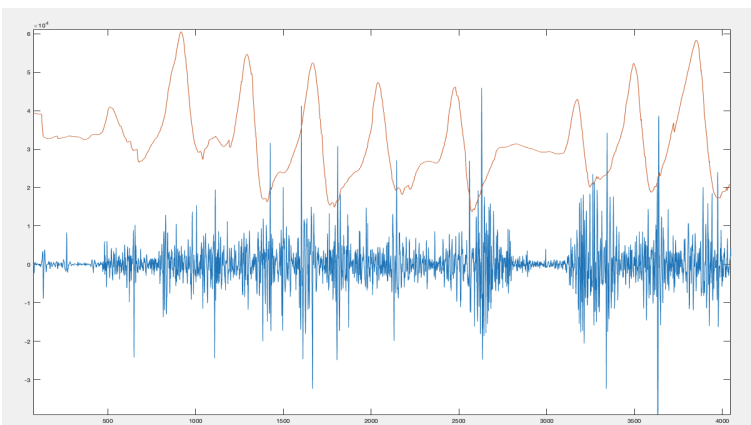


Figure 33: The blue line corresponds to the EMG measurement of Tibialis Anterior (TA) and the brown line corresponds to the knee angle.

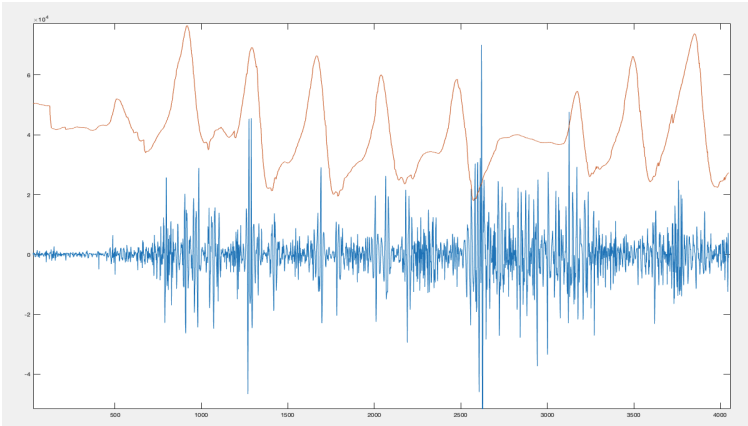


Figure 34: The blue line corresponds to the EMG measurement of Vastus Lateralis (VL) and the brown line corresponds to the knee angle.

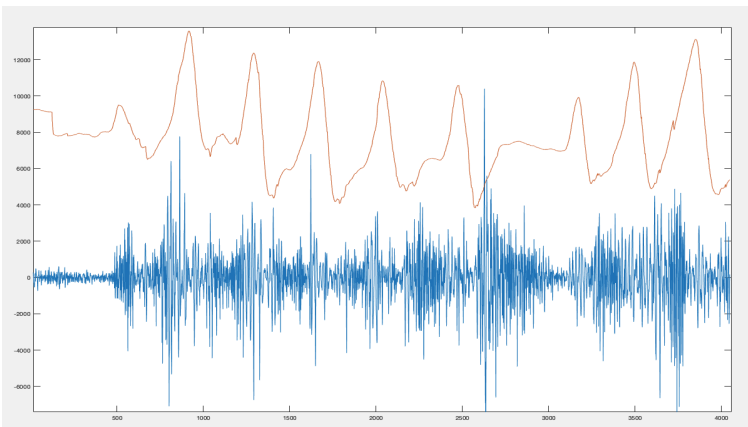


Figure 35: The blue line corresponds to the EMG measurement of Rectus Femoris (RF) and the brown line corresponds to the knee angle.

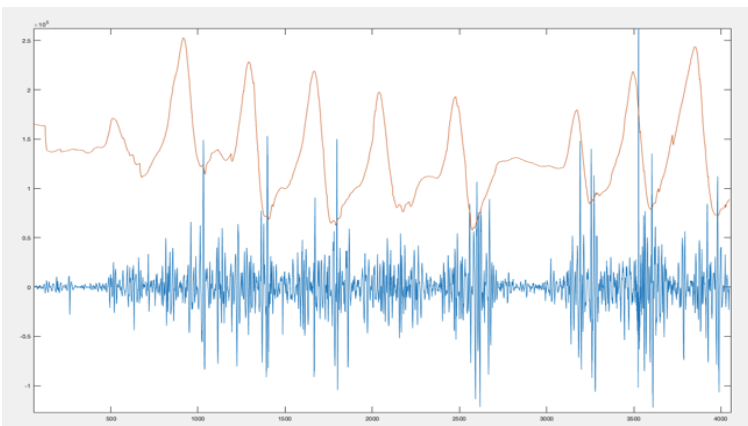


Figure 36: The blue line corresponds to the EMG measurement of Gastrocnemius Lateralis (GL) and the brown line corresponds to the knee angle.

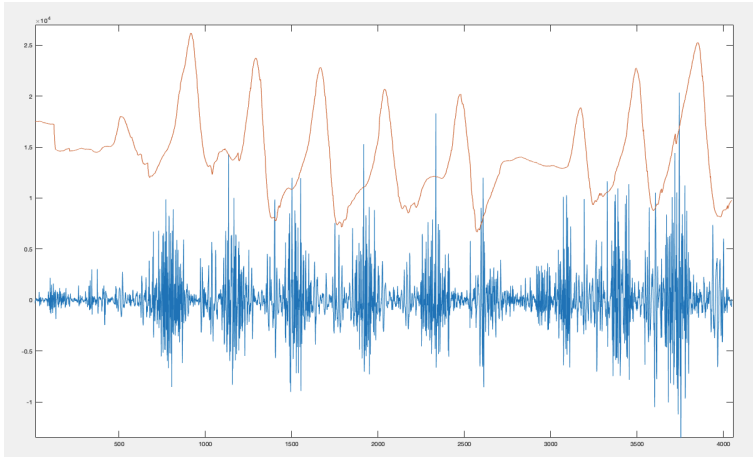


Figure 37: The blue line corresponds to the EMG measurement of Soleus and the brown line corresponds to the knee angle.

9. Future work and developments

The results obtained in this project are promising but there are still room for improvements. The attachments of the BNO080 sensors on the leg could be more stable. This can give a more accurate value of the knee angle. It is also essential to have in mind that the device should in the end be comfortable for a child to wear and not interfere with the daily activity of that child.

It was not possible to record for 24 hours due to some remaining problems with drifting signals probably caused by improper calibration of the IMU sensors. So, even more improvements in inertial angle measurements are needed. Test with different operational settings are also needed in order to reduce the errors in the recordings and maybe there might be need for more stable sensors.

It may be useful in future improvements to try and test different frequencies for IMU recordings. This can help to improve records for a more extended time period.

EMG recordings showed an excellent value that synchronized with measurements from the knee angle. The recording can be done with or without simultaneous recording of the knee angle.

The EMG recording in this project has been done for shorter time periods to compare with knee angle measurements. When the IMUs give more stable results over longer time periods, of course longer measurements with EMG should also be performed to ensure their long time performance.

Finally, an interface that facilitates the use of sensors for physicians and physiotherapists needs to be developed.

10. Conclusion

The development of the measurement of the knee angle has resulted in more reliable values. The drifting of the long time periods recordings has been significantly reduced. This increase the possibility to perform 24 hour measurements in the future. Further, the combination of knee angle measurements with EMG recordings of selected muscles gives exciting results.

11. Appendix

```
#include <Wire.h>
#include "SparkFun_BNO080_Arduino_Library.h"
#include <Adafruit_Sensor.h>
#include <math.h>
#include <SD.h>
#include <SPI.h>
#define ACTIVATED LOW
#define FILE_BASE_NAME "Data"
const int chipSelect = BUILTIN_SDCARD;
BNO080 myIMU; //Open I2C ADR jumper - Goes to Address 0x4B
BNO080 myIMU2; //Closed I2c ADR jumper - Goes to Address 0x4A
File myFile;
unsigned long id = 1;
int32_t k0=0;int32_t k1=0;int32_t k2=0;int32_t k3=0;
int32_t k4=0;int32_t k5=0;int32_t k6=0;int32_t k7=0;
long timeInterval = 10000;
long previousTime = 0;
const int buttonPin = 9;
int buttonState = 0;
unsigned long StartTime = millis();
int LED = 6;
const uint8_t BASE_NAME_SIZE = sizeof(FILE_BASE_NAME) -1;
char fileName[] = FILE_BASE_NAME "00.txt";
boolean deviceIDReturned = false;
boolean startedLogging = false;
byte incomingByte = 0;
byte measType = 0;
byte tPIN1 = 33;
byte tPIN2 = 34;
byte datahereIMU=0;
byte datahereEMG=0;
double relAngle;
#include <BME_ADS1299.h>
uint8_t CS = 10;
uint8_t DRDY = 24;
BME_ADS1299 ADS = BME_ADS1299(DRDY,CS,6000000);
void setup(void)
{
  Serial.begin(2000000);
  delay(100);
```

```

Serial.println(F("Relative angle measurement")); Serial.println("");
Serial.println(F("Initializing SD card..."));
Wire.begin();
if(myIMU2.begin(0x4B) == false)
{
Serial.println("Ooops, no BNO080 main sensor detected ... Check your
wiring or I2C ADDR!");
while(1);
}
if(myIMU.begin(0x4A) == false)
{
Serial.println("Ooops, no BNO080 second sensor detected ... Check
your wiring or I2C ADDR!");
while(1);
}
Wire.setClock(100000);
ADS.settings.device.samplingRate = 250; // Sampling rate 2 kHz
ADS.settings.channel[0].mux = 0; //Normal inputs = 0 (default). Shorted
= 1. Bias_meas = 2. Supply meas = 3. Temp meas = 4. Test signal = 5.
BIAS_DRP = 6. BIAS_DRN = 7.
ADS.settings.channel[1].mux = 0;
ADS.settings.channel[2].mux = 0;
ADS.settings.channel[3].mux = 0;
ADS.settings.channel[4].mux = 0;
ADS.settings.channel[5].mux = 0;
ADS.settings.channel[6].mux = 0;
ADS.settings.channel[7].mux = 0;
ADS.settings.channel[0].gain = 24; // Gain settings can be
1,2,4,6,8,12,24, default is 1
ADS.settings.channel[1].gain = 24;
ADS.settings.channel[2].gain = 24;
ADS.settings.channel[3].gain = 24;
ADS.settings.channel[4].gain = 24;
ADS.settings.channel[5].gain = 24;
ADS.settings.channel[6].gain = 24;
ADS.settings.channel[7].gain = 24;
ADS.settings.channel[0].pDn = 0;
ADS.settings.channel[1].pDn = 0;
ADS.settings.channel[2].pDn = 0;
ADS.settings.channel[3].pDn = 0;
ADS.settings.channel[4].pDn = 0;
ADS.settings.channel[5].pDn = 0;
ADS.settings.channel[6].pDn = 0;
ADS.settings.channel[7].pDn = 0;

```

```

ADS.settings.device.nDaisyChain = 1; // 0 = Daisy chain mode
(default), 1 = multiple readback mode
ADS.settings.device.intCal = 0; // Test source: 0 = external (default),
1 = internal
ADS.settings.device.calAmp = 0; // Test signal amplitude, see config
2 register in manual
ADS.settings.device.calFreq = 0; // Test signal frequency, see config
2 register in manual
ADS.settings.device.nPdRefBuf = 1; // Power down reference buffer,
0 = powered down (default), 1 = enabled
ADS.settings.device.biasRefInt = 1; // Biasref signal: 0 = Biasref
externally (default), 1 = Biasref generated internally
ADS.settings.device.nPdBias = 1; // Bias buffer power: 0 = buffer
powered down, 1 = buffer enabled
ADS.settings.device.compThreshold = 7; // Lead off comparator
thresholds see LOFF control register in manual
ADS.settings.device.iLeadOff = 1; // Lead off current magnitude: 0 =
6nA (default), 1 = 24 nA, 2 = 6uA, 3 = 24 uA.
ADS.settings.device.fLeadOff = 3; // Lead off frequency: 0 = DC lead
off detection, 1 = 7.8 Hz, 2 = 31.2 Hz, 3 = fs/4
ADS.settings.device.biasSensN = 1; // Bias Drive Positive Derivation
Register
ADS.settings.device.biasSensP = 1; // Bias Drive Negative Derivation
Register
ADS.settings.device.loffSensP = 0;
ADS.settings.device.loffSensN = 0;
ADS.settings.device.statusByte = 0;
ADS.settings.device.numChans = 1;
if(!ADS.begin())
{
Serial.println("Failed to start ADS, check connections");
while(1);
}
delay(100);
myIMU.enableRotationVector(1);
myIMU2.enableRotationVector(1);
myIMU.calibrateAll(); //enable dynamic calibration for accel, gyro,
magmyIMU2.calibrateAll();

if (ISD.begin(chipSelect)) {

Serial.println("initialization failed!");

return;
}

```

```

Serial.println("initialization done.");
while(SD.exists(fileName)) {
if(fileName[BASE_NAME_SIZE +1] != '9'){
  fileName[BASE_NAME_SIZE +1]++;
} else if (fileName[BASE_NAME_SIZE] != '9') {
  fileName[BASE_NAME_SIZE +1] = '0';
  fileName[BASE_NAME_SIZE]++;
} else {
  Serial.println(F("Can't create file name"));
  return;
}
}
myFile = SD.open(fileName, O_CREAT | O_WRITE);
if(!myFile) {
  Serial.println(F("Open failed"));
  return;
}
Serial.print(F("Opened: "));
Serial.println(fileName);
pinMode(buttonPin, INPUT);
digitalWrite(buttonPin,HIGH);
pinMode(LED, OUTPUT);
while(!digitalRead(9)) {
  digitalWrite(LED, HIGH); // turn the LED on (HIGH is the voltage level)
  delay(100); // wait for a second
  digitalWrite(LED, LOW); // turn the LED off by making the voltage
LOW
  delay(100);
}
pinMode(tPIN1, OUTPUT);
pinMode(tPIN2, OUTPUT);
}
void loop(void){
unsigned long CurrentTime = millis();
unsigned long ElapsedTime = CurrentTime - StartTime;

if (myIMU.dataAvailable() == true && myIMU2.dataAvailable() == true)
{
  digitalWrite(tPIN1,HIGH);
  datahereIMU=1;
  relAngle =
57.2958*2*acos(abs(myIMU.getQuatReal()*myIMU2.getQuatReal() +
myIMU.getQuatl()*myIMU2.getQuatl() +

```

```

myIMU.getQuatJ()*myIMU2.getQuatJ()+myIMU.getQuatK()*myIMU2.get
QuatK());
}
buttonState = digitalRead(buttonPin);
if(digitalRead(DRDY) == LOW)
{
    digitalWrite(tPIN2,HIGH);
    datahereEMG=1;
    ADS.updateData();
    k0 = ADS.adsData[0];
    k1 = ADS.adsData[1];
    k2 = ADS.adsData[2];
    k3 = ADS.adsData[3];
    k4 = ADS.adsData[4];
    k5 = ADS.adsData[5];
    k6 = ADS.adsData[6];
    k7 = ADS.adsData[7];
    digitalWrite(tPIN2,LOW);
}
if(buttonState == HIGH)
{
    digitalWrite(LED, HIGH);
    if (datahereEMG)
    {
        datahereEMG=0;
        datahereIMU=0;

        String dataString = String(id) + "," + String(ElapsedTime)+ "," +
String(relAngle)+
        "," + String(k0)+"," + String(k1)+"," + String(k2)+"," +
String(k3)+"," + String(k4)+"," + String(k5)+"," + String(k6)+"," +
String(k7); // CA added string to k1
        myFile.println(dataString);
        id++;
        Serial.println(dataString);
    }
    if(CurrentTime - previousTime >= timeInterval){
        myFile.flush();
        previousTime = CurrentTime;
        delay(10); }
}
else {
    digitalWrite(LED, LOW);
}
}
}

```

12. References

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