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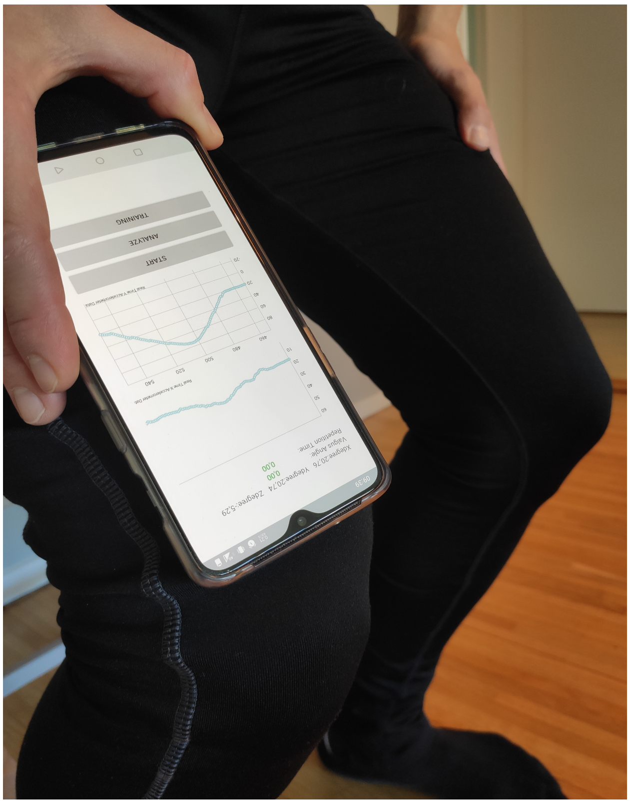

Direct feedback application for training with Osteoarthritis affected to the lower extremities

A smartphone application to improve patients compliance and empowerment during training

Master's thesis in Biomedical Engineering

EMELIE CARLBERG

DEPARTMENT OF PHYSICS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
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Supervisor: Magnus Karlsteen, Department of Physics
Examiner: Magnus Karlsteen, Department of Physics

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Department of Physics
Division of Material Physics

Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Photo taken during training with the application. Photo by Author.

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Abstract

This master's thesis covers the development of an application for patients and healthcare providers training to alleviate Osteoarthritis symptoms. The method used in this application to judge if the training is performed in a safe and correct manner is by using angles. These angles are measured using the smartphone accelerometers, magnetometer and gyroscope. These signals are used to provide direct feedback to the user, using Euler angles and a complementary filter.

The results indicate that the smartphone application can measure the angles of interest with good precision. There is still need for further development due to the problems of gimbal locking using Euler angles. Conclusions from the work is that there is great potential using the application both from a patient perspective and as a long term method for healthcare providers to follow up without physical visits.

Keywords: smartphone application, accelerometer, magnetometer, gyroscope, sensor fusion, direct feedback, osteoarthritis, training.

Acknowledgements

A big thanks to the team of physiotherapists Inger Björkenlid, Linnéa Dahlin and Monica Sommar, that have contributed with their knowledge during the whole process.

A big hug to my husband for the helpfulness, understanding and having such a large patience with me during this process.

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Emelie Carlberg, Gothenburg, May 2021

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Acronyms and Medical terms

Acronyms

OA	Osteoarthritis
WHO	World health organisation
ROM	Range of motion
ACL	Anterior collateral ligament

Medical terms

Valgus position	Knee tips towards the center of the body
Neutral position	Hip, Knee and ankle in a straight line
Varus position	Knee tips away from the center of the body
Femur	The name of the upper long bone
Tibia	The shinbone
Medial	To the middle of the body
Lateral	From the middle of the body

1
Introduction

Osteoarthritis (OA) is a joint disease, it leads to pain and disability every year for the affected and carry high costs for society [1, 2, 3]. It is one of the most common diseases [2], according to the World health organisation (WHO) it is one of the ten most common causes of disability among elderly people [3]. Nearly 10% of all men and 20% of all women over 60 years of age have problems due to OA [3, 4]. The disease can affect all joints in the body but the joints that take most of the body weight such as the hips and knees is represented in a higher volume [1]. An affected knee joint is illustrated in figure 1.1. There is no cure to the disease today, but treatments exist.

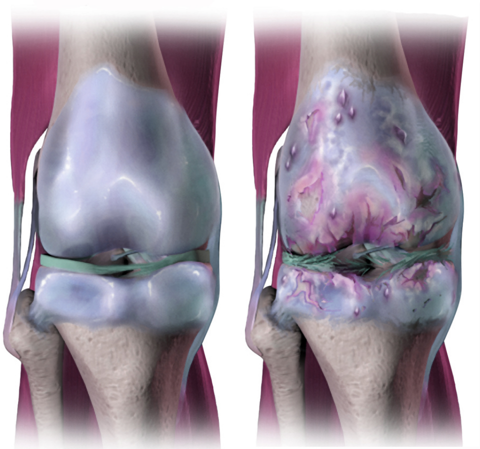


Figure 1.1: Knee osteoarthritis, left side normal knee, right side affected knee. Illustration free to use under Share Alike Creative Commons license 4.0 International license.
Available at: https://commons.wikimedia.org/wiki/File:Osteoarthritis.png

1.1 Treatment

The treatment of OA is divided into different stages, as seen in figure 1.2. In Sweden all patients will get information, personally fitted training and advice about weight loss according to the National Board of Health and Welfare [1]. To most patients it is enough with the first step [5], but if it is not, anti-inflammatory drugs and other analgesic methods can be used[1, 5]. The last resort, that very few patients need, is to undergo joint replacement surgery[1]. Around 80% of all patients do not need surgery [6]. It is of importance that the intervention is given in an early stage of the development of OA, today the median age of patients in the national program in Sweden is 67 years, that implies that the intervention may be a bit too late [6].

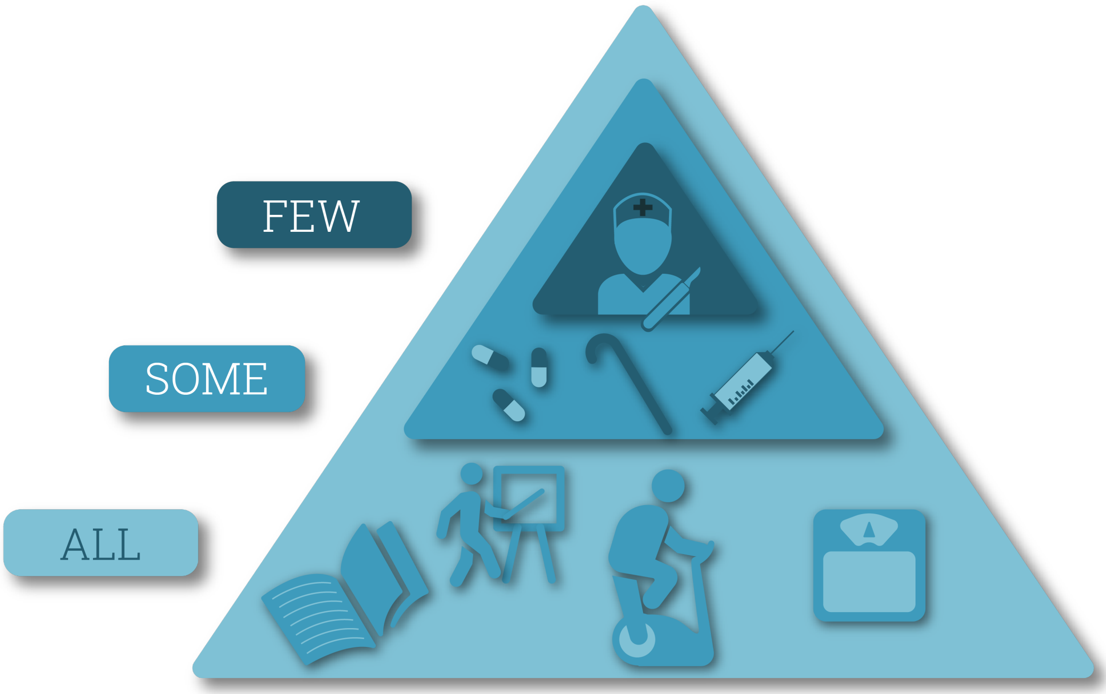


Figure 1.2: The Treatment-pyramid of Osteoarthritis. With permission to use, illustration by Signe Svensson.

There is a lifelong need for training as treatment due to OA [1]. The exercises should be carried out with good control daily to get the best effect [1, 7]. Control is measured by the parameters of up and down movement and the position of the knee. The position of the knee is of great interest, to observe and prevent valgus position, as this increases load on the joint [8, 9]. When the patients have supervision from a physiotherapist it is more common to follow the regime and perform the exercise correctly than when performing it on their own [1]. A problem is that it can be hard for the patients to know if they perform the exercise correctly when leaving the clinic. This is where a gap is seen today, there is a need of a simple tool to get both feedback over time and directly during training.

1.1.1 History

Joint problems have been known for a long time in old people [10]. At first it was an old mans disease, something that just older people got. The first way of treating OA was with joint replacement [10]. The understanding of the disease is better today but the mechanisms behind it are still not completely clear [10].

1.1.2 Today

The main non invasive treatment for OA is exercise [1, 11]. There are different programs from different countries and some difference if the hip or knee joint is affected [1, 12]. But the main goal to increase range of motion (ROM) and strength to the extremity is the same both for hip and knee OA [5, 13]. The importance is to build empowerment and focus on person-centered care, so that the patients own the possibility to change the outcome of the disease [7].

1.1.3 Upcoming

The future in treating OA may be to directly treat the joint with Mesenchymal stem cell injected or transplanted scaffold cartilage into the affected joint [14]. Treatment with injections involves an invasive part and a risk of infection, so it is not for everyone. Training and coping with the disease will likely be of high interest in the future, where technical solutions can play a big role.
There are some solutions where standard treatment of OA is web based, the effect of such programs differs [15, 16, 17]. It can be seen as a compliment or alternative to standard treatment in clinic, face to face [16]. The web based treatment can have effect on both pain and physical function [16, 18]. There is still a great need of trained medical professionals to give support to the patients during the rehabilitation.

1.2 Technical solutions

The need of a technical solution is big, due to the increasing elderly population and the incidence and prevalence of OA. The measurement systems that are on the market and used in clinic and research depends on a system of sensors or camera sensors [19]. The accuracy of the system is well proven but the downside is the physical size, amount of equipment needed and a trained person to analyze the results [19]. Joint motion can be detected and measured by the accelerometers in an ordinary smartphone [20]. But the phone used affects the outcome of the result [21]. The difference in a static test for different accelerometers in many phones shows that they differ [21].

1.3 Opening on market

There is a need of something for the patients to bring home to measure and easily control the training for empowerment and compliance during the life long rehabilitation. The parameters for movement control can be evaluated and controlled with a smartphone application, which should be easy to use for the patient. So the aim of this project will be to construct a smartphone application to measure and give direct feedback during training to patients suffering from OA.

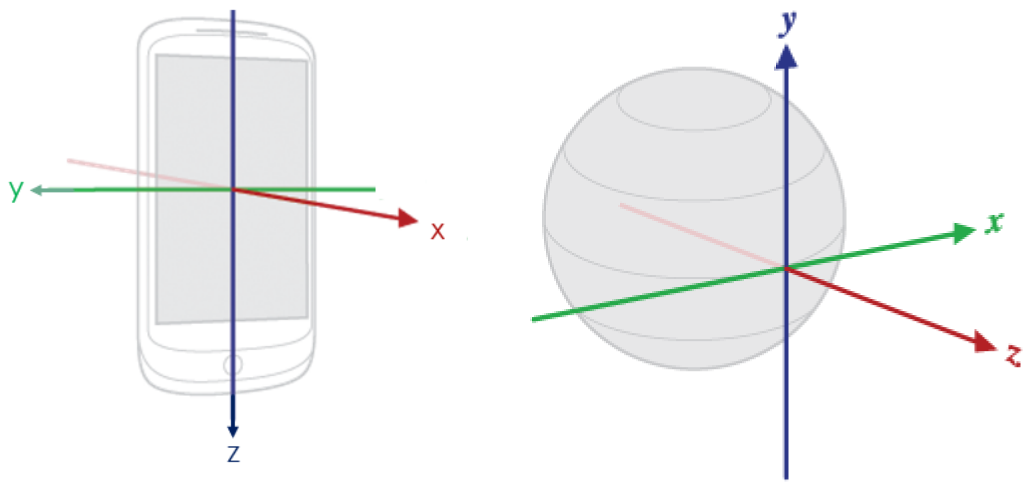
This project will be held in collaboration with Chalmers University of Technology, Swedish University of Agricultural Sciences, SLU and Sahlgrenska University Hospital. (Sahlgrenska Academy at University of Gothenburg)

2
Theory

The theory behind a motion sensor system built upon integrated sensors in a smartphone needs some knowledge about the different sensors, how to perform sensor fusion, some different approaches to position tracking and how to filter the data.

2.1 Coordinate system

There is a difference between the smartphone coordinate system and the global coordinate system, as seen in figure 2.1[22]. The smartphone coordinate system is bound to the phone and will remain stationary relative to the phone. The earths coordinate system is fixed to the earths inertial frame of reference [22]. To get the change in orientation of the phone relative to the earth a rotation matrix is needed [22].



(a) Phone coordinate system (body coordinate)

(b) Earth coordinate system (world coordinate)

Figure 2.1: The different coordinate system to combine. Portions of this page are reproduced from work created and shared by the Android Open Source Project and used according to terms described in the Creative Commons 2.5 Attribution License. Available at: https://developer.android.com/guide/topics/sensors. Modified by Author.

To rotate the different coordinate system the basic elemental rotation around the three axes, x , y and z, is applied [22, 23, 24].

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{bmatrix} \tag{2.1}$$

$$R_y(\beta) = \begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix} \tag{2.2}$$

$$R_z(\gamma) = \begin{bmatrix} cos\gamma & -sin\gamma & 0 \\ sin\gamma & cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.3}$$

Where the total rotation matrix is given as [22, 23, 24]:

$$R = R_x R_y R_z \tag{2.4}$$

with the given equations above [22, 23, 24]:

$$R = \begin{bmatrix} cos\gamma cos\beta - sin\alpha sin\beta sin\gamma & sin\gamma cos\alpha & cos\gamma sin\beta + \sin\gamma sin\alpha cos\beta \\ -cos\beta sin\gamma - sin\alpha sin\beta cos\gamma & -cos\gamma sin\alpha & cos\gamma sin\alpha cos\beta - sin\gamma sin\beta \\ -cos\alpha sin\beta & -sin\alpha & cos\alpha cos\beta \end{bmatrix} \tag{2.5}$$

The rotation matrix results in a 3D orientation of the coordinate system.

2.2 Sensors

To build a measurement system for body movement a combination of different sensors need to be involved [22, 25]. The ones used in this work is accelerometer, gyroscope and magnetometer. The data from these sensors often need filtering to get accurate results.

2.2.1 Accelerometer

The accelerometer can be illustrated as a mass spring system. The accelerometer is based on Hooke's law (2.6) and Newtons second law (2.7), as following[25]:

$$F = kx \tag{2.6}$$

Where F is force, k is spring constant and x is displacement of the object attached to the spring. And Newtons second law [25]:

$$F = ma \tag{2.7}$$

Where F is force, m is mass and a is acceleration. From these two equations the expression for acceleration is given as:

$$a = \frac{kx}{m} \tag{2.8}$$

In a smartphone acceleration is measured in g, the gravitation constant [26]. If the smartphone is placed on a flat surface, it will show +9.81 in acceleration, this is due to the gravity component influencing the phone as [26]:

$$a = -g\frac{-\sum F}{m} \tag{2.9}$$

The accelerometer sensor in the smartphone detects acceleration in x, y and z direction, hence there is one accelerometer in every direction [23, 25]. The accelerometer is sensitive to motion of the smartphone, and will send a lot of information but the signal is also influenced of the gravity and noise.

2.2.2 Gyroscope

There are different types of gyroscopes [23], the one used in small units is commonly a vibrating mass gyroscope [25]. The gyroscope measures angular velocity or displacement of angular velocity [24]. The vibrating gyroscope is built upon Coriolis effect [24, 25]:

$$\boldsymbol{F}_C = -2m(\boldsymbol{\omega} \times \boldsymbol{v}) \tag{2.10}$$

Where F is force, m is the mass, $\boldsymbol{\omega}$ is the angular velocity and $\boldsymbol{v}$ is the relative velocity to the object [25].

A problem that can occur with gyroscopes, is gimbal locking, this commonly happens at 90°, to prevent the problem there can be a rotation limiter at 85°of rotation of the inner gimbal [24]. This is a mathematical problem when using Euler angles for the rotation matrix, a solution is to use quaternions instead [27].

The gyroscope sensor drifts over time, this is due to changes in the rotation, procession, caused by imperfections in the sensor [24]. The signal gets integrated and over time the signal drifts, there is a need of filtering to minimize this issue [24].

2.2.3 Magnetometer

The magnetometer is used like a compass to the motion sensor. The problem with the magnetometer is that it picks up local magnetic fields, both inside the phone and outside as well as the earths magnetic field [23]. This means that even this supposedly stable signal is influenced by noise.

2.2.4 Sensor fusion

The different sensors in combination gives a more accurate signal [23, 25]. The accelerometer gives the direction, the gyroscope the rotation and the magnetometer helps the gyroscope to avoid drift over time [23, 25]. However the problem with noise from the signals remain, as for the magnetometer it is influenced by all surrounding magnetic fields (electronics, magnets), the accelerometer picks up all motion and white noise, the gyroscope has the risk of gimbal locking [25]. The sensor fusion needs to be tackled with filters to eliminate the different offsets, a basic setup is shown in figure 2.2.

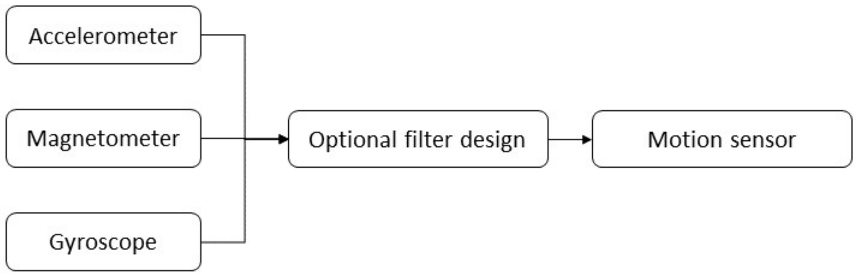


Figure 2.2: A basic setup for sensor fusion and optional filtering of the signals from the three different sensors. Illustration by author.

2.3 Filtering

The need of filtering for the signal is of great proportions, otherwise the signal will consist of noise, drift and integration error accumulation. The filters used or studied will be presented below.

2.3.1 Kalman filter

When integrating acceleration to velocity or to get displacement a good filter design is a must. There needs to be reduced noise and disturbance signals due to described problems with integration in section 2.4.1. Kalman filtering can reduce the offset due to integration of the signal from 68% unfiltered to 9% filtered [28]. Filtering integrated acceleration signals to calculate human displacement have previously been done with good accuracy using Kalman filtering [29, 30]. It is however hard to implement the filter and it is processor intensive [31].

2.3.2 Complementary filter

A complementary filter design is another approach to minimize disturbance. The accelerometer data is combined with the magnetometer, low-pass filtered and the gyroscope signal, angular velocity, is integrated to get the gyroscope orientation and high-pass filtered [31]. These signals sum up to the output angles. The name complementary origins in that the two parts shown in figure 2.3 complement each other [31]. The low-pass filtered data is used to reduce the gyroscope drift [31].

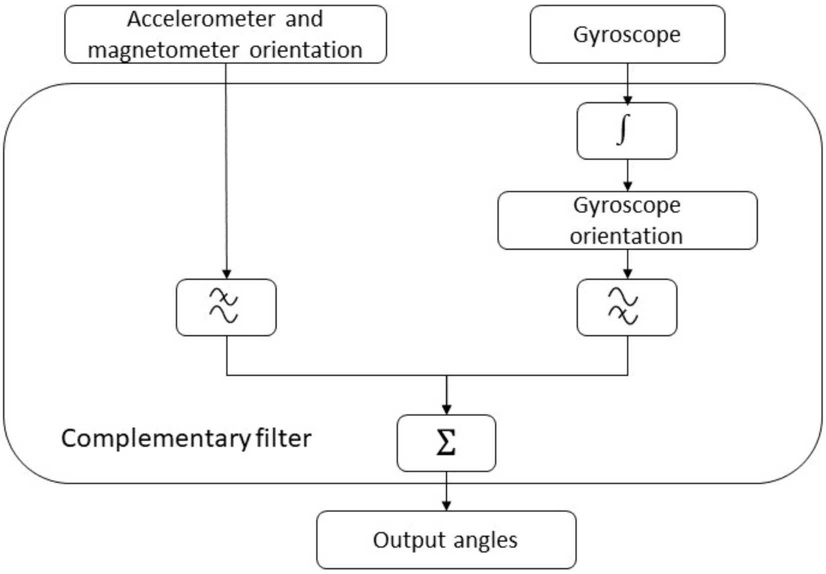


Figure 2.3: Sensor fusion and filtering of the signals from the three different sensors by complementary filter design. Illustration by author.

Complementary filters are commonly used in smartphone applications, due to the low need of processing capacity [31]. The implementation of the output angle in code for around the x-axis:

```
output_angle[x]  = filter_parameter * gyro_orientation[x] +...
...+ (1 - filter_parameter) * acceleration_magnetometer_orientation[x]
```

The calculation for output angle needs to be performed for every axis, x, y and z. The filter parameter needs to be adjusted to fit the smartphone used. The output angles will be in radians and need to be converted to degrees.

2.4 Position tracking

For position tracking there are different approaches available. Two common approaches is to go for integration of the accelerometer data or calculate the rotation angles.

2.4.1 Integration

In the smartphone there are no sensors or possibilities to get velocity or displacement directly. The acceleration data available needs to be integrated one time to get velocity (2.11) for the up and down movement of the exercises and twice to get displacement (2.12), for the position of the knee, the valgus displacement. This signal however is influenced by a lot of noise, integration of such a signal can be problematic [23].

$$v(T) = \int_0^T a(t)dt = \lim_{n\to\infty} \frac{T}{n} \sum_{s=1}^{n} a(t_s) \tag{2.11}$$

$$d(T) = \int_0^T v(t)dt = \lim_{n\to\infty} \frac{T}{n} \sum_{s=1}^{n} v(t_s) \tag{2.12}$$

The problem with integration of the signal is that the noise and errors also get integrated and grows over time, in quadratic speed due to the integration needed to get displacement [23]. The need of double integration makes it important to construct a robust integration procedure. Another problem is the estimation of gravity, when it gets integrated a large error is implemented with just a small angular deviation [23].

2.4.2 Rotation with Euler angles

Euler angles is a common way to calculate angles from sensor data. The angles are called, roll (around x-axis), pitch (around y-axis) and heading (around z-axis) [25]. The Euler angles can be computed from the rotation matrix in equation 2.5, the angle is the difference in rotation between the coordinate systems described in section 2.1 [32]. When the local coordinate system of the phone gets close to plus minus 90°of a certain axis (in this case around y-axis) the system fails, this is due to singularities caused by gimbal locking [24, 25]. Quaternions is a $\mathbb{R}^4$ way of describing angles in $\mathbb{R}^3$ and eliminates the risk of gimbal locking [27].

2.5 Bio-mechanical load

The position of the knee can be neutral, valgus or varus described in figure 2.4. The position affect the loading of the knee, the tibia plateau. The medial part takes the load in varus and the lateral in valgus [8, 9]. Valgus alignment of the knee increases the risk of OA [8]. The displacement in degrees between 1.1 to 3 degrees results in higher risk of developing OA, and progression of the disease [9]. These measurements were done in long leg x-ray [9], not during activity, hence other angles needs to be used as offset angles in this project.

(a) Neutral position of the knee

(b) Valgus position of the knee

(c) Varus position of the knee

Figure 2.4: The three positions of the knee, neutral, valgus and varus position, where the increased pressure on the different plateau can be seen as decreased distance between femur and the tibia plateau. Illustration used according to terms described in the Creative Commons CC0 1.0 Universal Public Domain Dedication. Available at:
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https://upload.wikimedia.org/wikipedia/commons/5/5d/Genu_varum.svg,
https://upload.wikimedia.org/wikipedia/commons/9/90/Genu_valgum.svg

3
Methods

The different steps in constructing the application and the validation of the application will be presented in the next chapter. During all of the development, three clinical active physiotherapist have put their knowledge into the application, Inger Björkenlid, Linnéa Dahlin and Monica Sommar.

3.1 Development of application

The programming language used was java programmed in Android Studio version 4.1.2. The code is influenced and based on the Android developer guides, Motion sensors [26]. The application was built to work on a Xiaomi MI model:M1903F2G.

The development started with addressing the issue of interest, an objective way to measure motion in patients with OA. The development process is shown in a overview in figure 3.1.

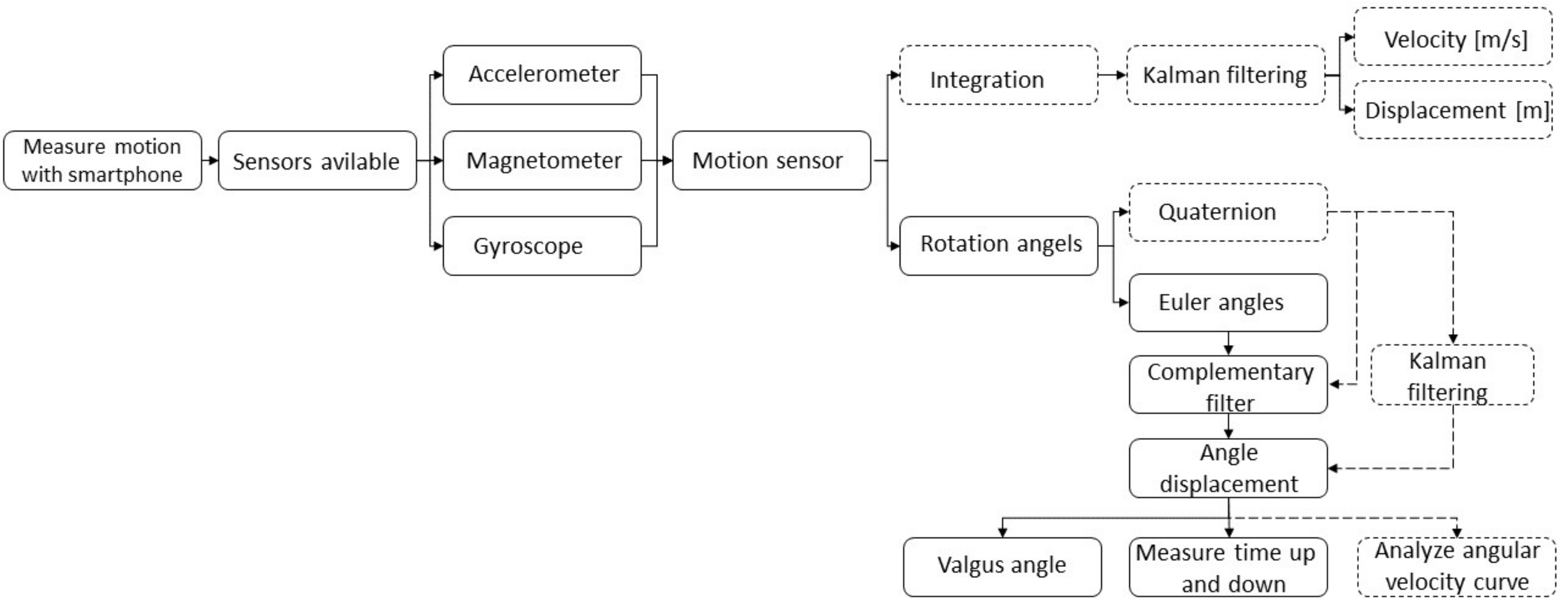


Figure 3.1: Illustration of application development, full contours the way development turned out and dashed alternative tested or investigated during development process. Illustration by author.

After addressing the problem of training with OA, an overview of the market potential was done. Then the question of what is available to work with in the smartphone need to be answered. The three sensors of interest, accelerometer, magnetometer and gyroscope was further investigated. At first the thought was to go for velocity and displacement in meters. That track was followed for a while. Then it was realized that rotation angles would fit the need better and that track was analyzed. There are different ways to approach the rotation angles such as Euler angles and quaternions. The signals can be filtered in different ways. The complementary filter was chosen and angles of displacement around x-axis is used to measure the position of the knee and around y-axis to measure time up and down to set boundaries for the parameter control. There is a possibility to investigate the angular velocity curve to make a judgment if the patient is performing the motion in a controlled fashion or not.

3.1.1 System design

When using the application the start screen will be the standard mode, training screen. There the user can go to advanced mode or analyze using the button, "Advanced Training" or to "Analyze". To begin measurement the user should click "Start Training", this calibrates the angles and starts measurement of the movement. The illustration in figure 3.2 shows the system design of the application.

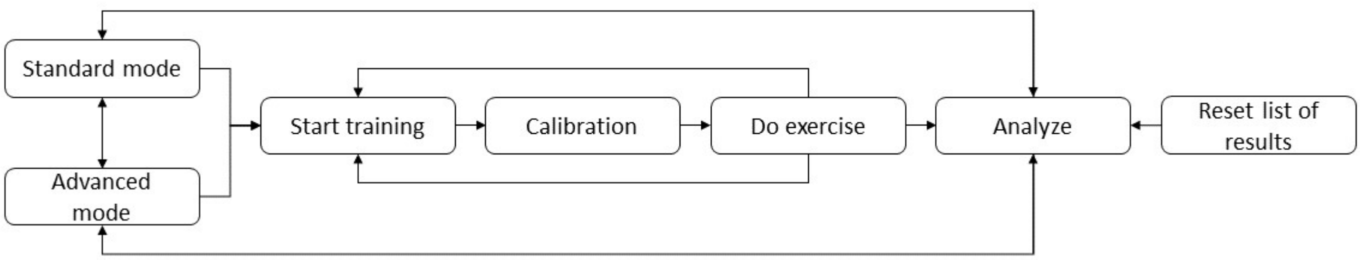


Figure 3.2: The system design illustrated. Illustration by author.

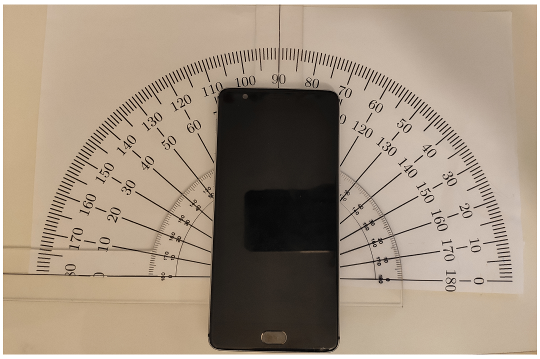
The calibration is done by subtracting the current input when initializing the calibration, so the angles are measured relative to the calibration position. During the training the user will get information in green or red numbers. After the training is done the user can go to analyze to get an overview of the training results. The user then need to reset the list if an other set of repetitions will be performed and analyzed. There is no option to save your results in the application at this time.

3.2 Validation

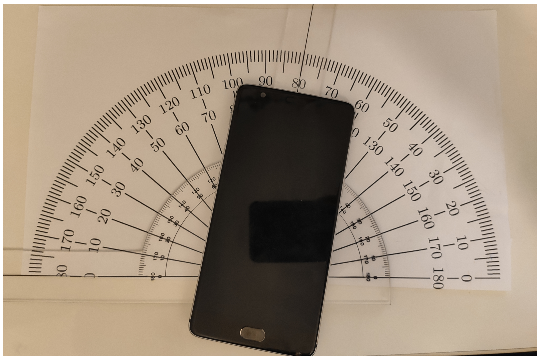
There is a need for validation of the precision of the application, this validation is performed in two steps. One with the smartphone on a table and the other in action.

3.2.1 Protractor validation

For the first step in validation of the application a protractor is used. The device is moved in different angles and then back to original position to get the accuracy of the measurements. The positions used around the x-axis is plus and minus of the following angles; 0°, 5°, 10°and 15°. This test is repeated 10 times. An illustration of the test setup is shown in figure 3.3.



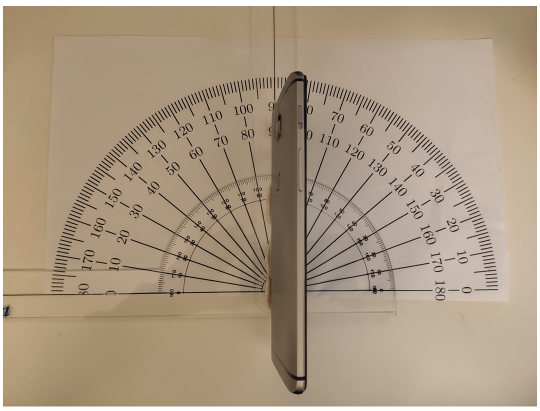
(a) Illustration over validation at 0°



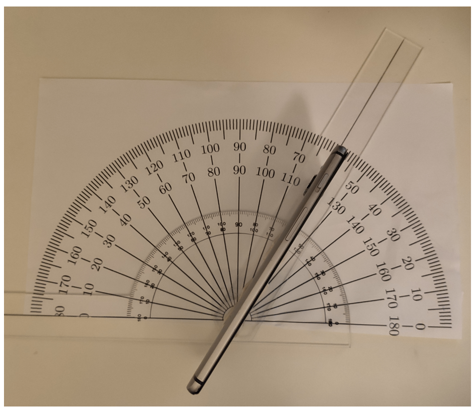
(b) Illustration over validation at 10°

Figure 3.3: Illustration over the validation process around the x-axis. Illustration by author.

The positions used around y-axis is the following angles; 0°, 30°, 60°and 90°. This test is repeated 10 times. An illustration of the test setup is shown in figure 3.4. The difference of angles tested around x- and y-axis is due to the nature of the possible movement in valgus or up and down.



(a) Illustration over validation at 0°



(b) Illustration over validation at 30°

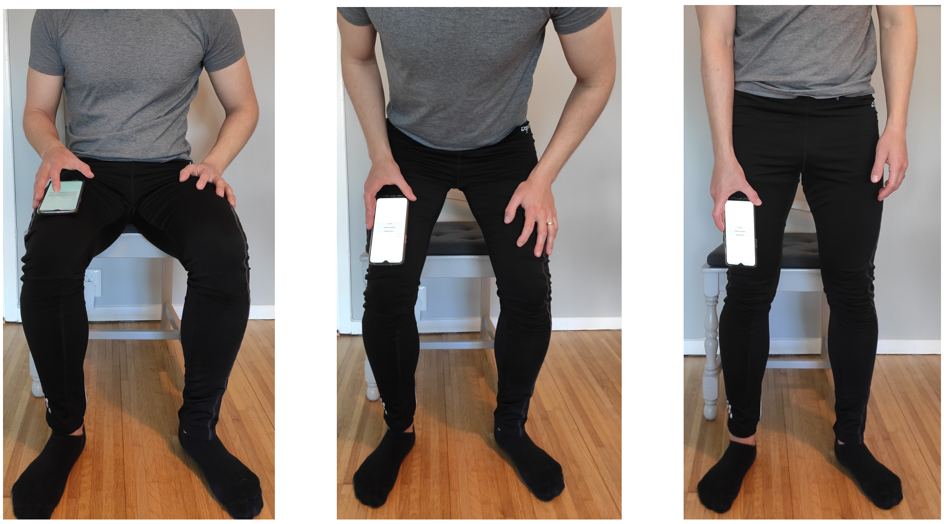
Figure 3.4: Illustration over the validation process around the y-axis. Illustration by author.

3.2.2 Squat time validation

To validate if the application measures the time for a completed squat correctly, a visual approximation of the squat was compared with the result from the application. The time starts when the test person starts rising from the chair and stops upon return to the seat. This to be able to make a judgment upon control around the y-axis.

3.2.3 Activity validation

The highest priority is that the application works during training, the next validation step is to see if it works during active movement, the test-setup is shown in figure 3.5. To calibrate the boundaries a first trial with 8 squats was analyzed by the team of physiotherapists on film. After that a test subject will do three sets of 10 repetitions of squats that will be filmed. The team of physiotherapists will independently judge the squat according to the two parameters; control of valgus position and up and down movement. Then the result from the application will be extracted and compared with the visual subjective judgment.



(a) Calibration **(b)** In activity **(c)** Top position

Figure 3.5: Illustration over the activity validation process. Illustration by author.

3.2.4 Usability

To evaluate the usability of the application qualitative parameters will be extracted, from the team of physiotherapists using the application. The result will be a compilation of what the team said during the test of the application, divided into subsections extracted from the communications.

4

Results

The application and the validation results will be presented in the following chapter.

4.1 Application

The application programmed in this thesis work is showcased in the three screens as mentioned in the method section, training screen, figure 4.1, advanced training screen, figure 4.2 and analyzing screen, figure 4.3. The first screen is a simple and clean screen, where the knee position and repetition time is shown, the values of performance will turn red if repetition is out of boundaries and stay green if the exercise is performed well. The "Start Training" button zeroes the angle measurement so that the deviation angles can be calculated and shown as results. The user has the possibility to go to the advanced training screen or analyze the results of the set of repetitions previously performed.

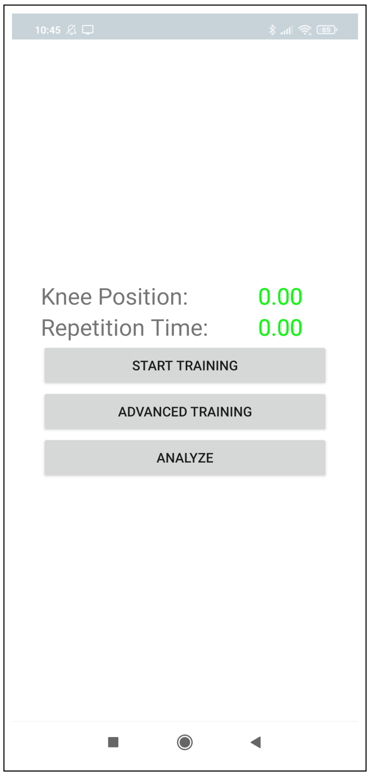


Figure 4.1: The launch screen, also called training screen. Illustration by author.

The screen in advanced mode figure 4.2 shows more data with angle plots in real-time and the angular deviation curve for the x- and y-axis. Here "Start" is the zeroing button. At this screen it is also possible to go back to the launch screen, training screen, or go to the analyze screen where the list of performed squats is shown.

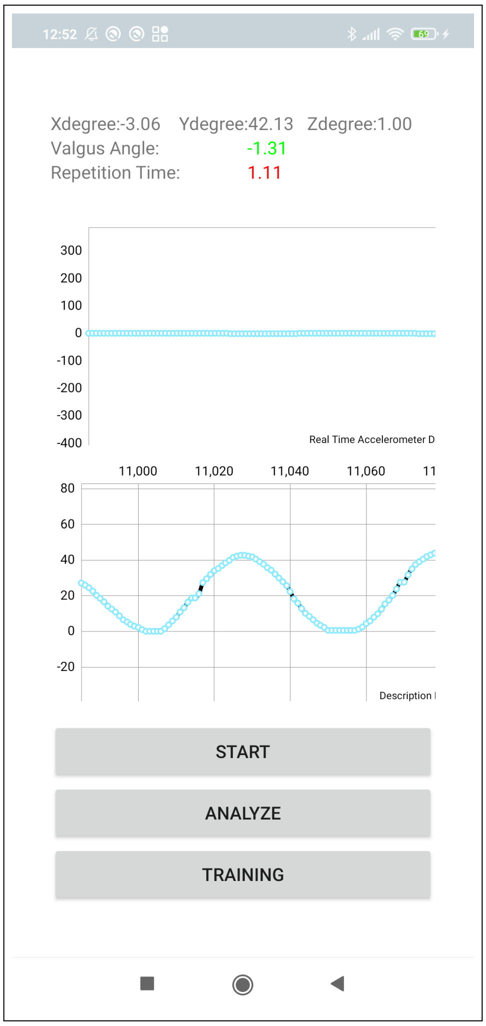


Figure 4.2: The advanced training screen. Illustration by author.

At the analyze screen, figure 4.3, the user can see all results from the training in list form. Due to regulations with saving data there is no possibility to save the results in the application, yet. The user can reset the list and start a new set of exercise when desired or continue and keep the previous results until visiting the screen again.

Figure 4.3: The analyze list screen. Illustration by author.

4.2 Validation results

The results from the different validation steps will be presented in this section.

4.2.1 Protractor validation

The results from the protractor validation is presented in the following tables. The first table contains the validation around x-axis in positive direction, table 4.1 and around x-axis in negative direction is seen in table 4.2. At the last two rows in both tables the average measured angle and the average differentiation is presented. The large offset both in positive and negative direction occurred when returning to starting position, this implies that there could be a need for calibration between sets.

Deg / Rep	0°	5°	10°	15°	0°
1	0	4.1	10.5	14.4	-8.8
2	0	5.4	11.5	15.3	-3.3
3	0	4.7	10.6	16.2	-0.5
4	0	5.0	11.6	15.9	0.9
5	0	5.3	11.2	15.9	0.2
6	0	5.6	10.8	14.8	0.9
7	0	3.8	11.8	14.2	-4.2
8	0	4.3	9.6	13.3	-1.8
9	0	6.4	11.9	14.4	-2.1
10	0	4.0	9.0	14.8	-2.5
Average angle	**0**	**4.86**	**10.85**	**14.92**	**-2.12**
Average diff	**0**	**-0.14**	**0.85**	**-0.08**	**-2.12**

Table 4.1: Results of protractor validation around x-axis in positive direction measured in degrees.

Deg / Rep	0°	-5°	-10°	-15°	0°
1	0	-5.2	-10.7	-16.1	0.3
2	0	-4.5	-8.2	-12.4	2.3
3	0	-4.3	-10.1	-14.6	1.6
4	0	-5.6	-10.0	-14.5	1.1
5	0	-4.5	-9.0	-13.2	1.6
6	0	-5.4	-9.8	-14.9	0.6
7	0	-4.7	-8.6	-14.3	1.1
8	0	-4.2	-9.4	-15.5	0.6
9	0	-4.8	-8.8	-13.4	1.6
10	0	-4.5	-8.6	-13.2	1.5
Average angle	**0**	**-4.77**	**-9.32**	**-14.21**	**1.23**
Average diff	**0**	**-0.23**	**-0.68**	**-0.79**	**1.23**

Table 4.2: Results of protractor validation around x-axis in negative direction measured in degrees.

For the validation around y-axis the results is presented in table 4.3. At the last two rows the average measured angle and the average differentiation is presented. Around the y-axis the biggest offset is about 90°, which is expected as it is at the largest deviation from origin.

Deg / Rep	0°	30°	60°	90°	0°
1	0	30.2	57.7	87.8	0.6
2	0	30.4	57.3	87.4	-0.1
3	0	30.1	57.2	87.7	-0.2
4	0	30.4	58.9	88.6	-0.4
5	0	30.6	58.6	88.6	0.2
6	0	30.3	57.9	89.7	-1.0
7	0	30.2	60.0	87.8	0.2
8	0	29.9	59.2	86.9	0.2
9	0	30.0	57.6	87.2	-0.2
10	0	29.8	58.2	87.4	0.1
Average angle	**0**	**30.19**	**58.26**	**87.91**	**-0.06**
Average diff	**0**	**0.19**	**-1.74**	**-2.09**	**0.06**

Table 4.3: Results of protractor validation around y-axis measured in degrees.

4.2.2 Squat time validation results

The repetition time results in seconds is shown in table 4.4. At the last row an average differentiation between the clocked time using visual judgment and the time the application calculated. The average difference is 0.097s.

Rep	application	clocked
1	2.67	2.98
2	2.76	2.69
3	2.55	3.01
4	2.73	2.99
5	2.82	2.71
6	3.0	2.88
7	2.79	2.97
8	2.64	2.54
9	2.67	2.66
10	2.52	2.69
Average diff	**0.097**	

Table 4.4: Time difference between application measured squat-time and clocked time in seconds.

4.2.3 Activity validation

The results of the activity validation is presented in the following tables, where green is good performance and red failure, app stands for application results and PT for physiotherapist. The results is presented in the tables 4.5 to 4.10. There is a clear difference between the application and the physiotherapist judgment. The conclusions from the observations are not unanimous among the physiotherapists.

Rep	App	PT1	PT2	PT3
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Table 4.5: Repetition time set one

Rep	App	PT1	PT2	PT3
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Table 4.6: Knee position set one

Rep	App	PT1	PT2	PT3
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Table 4.7: Repetition time set two

Rep	App	PT1	PT2	PT3
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Table 4.8: Knee position set two

Rep	App	PT1	PT2	PT3
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Table 4.9: Repetition time set three

Rep	App	PT1	PT2	PT3
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Table 4.10: Knee position set three

4.2.4 Usability

The results from the response from the team of physiotherapists is divided into different subsections below.

4.2.4.1 Need for an application

The group of physiotherapist is unanimous when evaluating the application. There is a need in clinic for such an instrument. It would be usable both for professionals and patients, they say. The application could be useful in other patient categories as well, such as for patients suffering from an anterior collateral ligament (ACL) injury. It could also be a big motivator for the patients to keep on training at home, building up empowerment on their own.

4.2.4.2 Technical comments

The group commented that they can not see a problem with the small deviation in the protractor validation results. They state that they can not see the difference in a couple of degrees. They also see a need to do studies about boundary conditions and analysis of what a good or bad performance is for different exercises and injuries.

4.2.4.3 Parameter control

As the application is implemented today they can see a problem with that there is no way to measure how much weight is placed on the different legs, the patient could be doing a very unsymmetrical squat and still get a pass from the application. When the physiotherapists evaluates the performance they mentioned that the control can be good overall, a green result, but they would have corrected the test subjects performance for example at the end of the exercise not to drop to the seat, something that is not captured by timing alone.

5
Discussion and Conclusion

The main issues with this application and analysis of the movement comes from the implementation of Euler angles and the fact that a smartphone is only one set of sensors and not two or more to measure both legs. There will also be some discussion about other uses for the application and future areas of improvement to work with.

5.1 Discussion

In this section discussions about the technical limitations of the thesis as well as some issues and areas of improvement.

5.1.1 Angles of interest

To validate if the patient performs the exercise both with control in up and down movement and does not fall into valgus position, two angles are measured. The angle used to evaluate valgus position is small, ranging only plus and minus four degrees from origin for an approved squat, meaning that the margin of error in measurement is low. The angles to evaluate and calculate the time for up and down movement is larger but needs to be stable as well.

Due to gimbal locking the system becomes unstable when in the standing position, this is making the measurement of the valgus angle unstable, sometimes giving 180 degrees deviation from origin even if the angle did not change that much. This problem can be solved by stopping the measurement near the top part of the movement. This limitation will probably not influence the measurement of the valgus position as it is not so common to fall into valgus position when the leg is straight. However measurement must begin on the way down again to make sure valgus position is avoided. The problem of gimbal locking when using Euler angles is probably best solved by using quaternions instead [27]. However Euler angles have presented reliable results in all angles except at the standing position.

5.1.2 Control is a hard parameter to analyze

The way to check if the exercise is performed in a controlled fashion is to measure the time to finish the movement. This is done by starting a timer upon rising and stopping the timer when reaching the seated position again. Setting boundaries for time to complete the movement was a solution to get a working application during the thesis. A more effective way to analyze whether or not the user performs the movement with control is to measure the smoothness of the curve for the angular velocity around the y-axis. Using this approach it would also be possible to see what part of the movement the patient is having trouble keeping the same speed as the rest of the movement.

5.1.3 Technical limitations

The scope of the thesis is limited to just one phone model. The problem of using sensor data with different phones is the need of different filter parameters due to differences in the sensors between phone models. This is a known problem and could not be solved in the frame of this thesis.

The sensors the system is built upon is an other issue, the accuracy and disturbance from other signals. The magnetometer can have problems indoors due to other magnetic fields it can pick up. The accelerometer data have a lot of noise in the signal. The filtering can attenuate signals of interest, and the noise can give false result. The gyroscope drifts and need filtering and correction using the magnetometer to get a stable signal. The results can however be assumed to be mostly correct after filtration [33], the results from this report also indicate the same conclusion.

5.1.4 Complementary or Kalman filter

The complementary filter used in the application do have similar results as for a more advanced filter type as the Kalman filter [31]. A complementary filter is easy to adjust with only one parameter compared to the Kalman filter [31]. For this application the precision of the complementary filter have proven to be good enough.

5.1.5 Precision for science

If the device is to be used as a scientific tool to measure training with OA there is a possibility to increase the accuracy with the Kalman filter approach and usage of quaternions [31]. The information available can be increased by adding sensors as well [27, 34], the system will be more complex than the smartphone alone. With a more complex system, there will be a need for the patients to purchase another device [34].

5.1.6 Sensitive to updates

The application as implemented today is sensitive to updates of the smartphone operative system as have been discovered during the development process. After an update the filter parameters might need to be adjusted to have a stable system again.

5.1.7 Validation process

During the validation process two problems arose. First movements around x-axis had some problem going back to origin. The angles around y-axis became very erratic when the phone was at 90 degrees due to the phenomenon of gimbal lock. Both problems would probably be solved by using quaternions.

The validation during activity gave varying results, both from the application and internally in the group of physiotherapists. This implies that the application could be of great use even for physiotherapists. Another reason for the discrepancy between the physiotherapists judgments could be that they had to evaluate the movements by film, something that could trick the eye. Allowing only one viewing angle which is the case when filming from the front is not optimal for visual judgment.

5.1.8 Other areas of interest

The application could be used for other areas and injuries where rehabilitation is made using similar parameters as for OA. One such example could be ACL-injuries that the physiotherapists brought up during discussion about the application. It might require different boundary angles meaning that you might need to select what type of training you want to use the application for when starting it.

5.1.9 Opening on the market

There are statements from different actors showing that web-based treatments can be an effective alternative to treat patients with OA [16, 18]. The next step for internet-based training could be to receive direct feedback during training. It would increase efficiency and lead to increased empowerment for the patients, increasing likelihood of continuing with the training.

5.2 Future work

For future work a dot list is presented:

- Change structure to quaternions
- Implement and analyze the angular velocity curve for evaluation of control
- Interface layout
- Implement for different exercises and injuries
- Get better boundary conditions and implement for different exercises
- Test the application in clinic

5.3 Conclusion

The application constructed during this masters thesis could work as a tool during training for patients suffering from OA. Not least to build empowerment during training at home. And work as an objective measurement tool for health care providers during examination of movement. There is a need of further development for parameters like control and make the implementation of quaternions to take it to the next level. This application can be seen as a proof of concept, there is a possibility to help patients suffering from OA during training with this type of application.

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