The detection of (in)correct motion during resistance training

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***Abstract*—In this research a framework in Matlab is developed, which identifies the incorrect body motions of a squat using inertial measurement units. Regarding this development, certain research questions arises. First, what are the quality metrics of resistance training? Secondly, to what extent can IMUs detect those metrics, and what is the quality of this detection?**

Two personal trainers and a sport physiotherapist are interviewed, to determine which exercises are important and have a high chance on injuries. Based on the outcome of the interviews, literature is used to identify the quality metrics of the most common exercise, the squat. Those metrics are used to design the process chain and output of the framework. The algorithm uses the Euler angles of the limbs as input. The end application is able to detect the timing of a squat, the angle made by the trunk and the angle made by the knee joints. Optical measurements, using the software Kinovea, are done to validate the algorithm. Based on the validation the algorithm results deviate significantly from the optical measurements. The timing algorithm has an error of maximum 0.2 seconds. Moreover the obtained angles have a maximum error of 22 degrees. In the recommendation section, it is proposed to use acceleration data for decreasing the timing error. To decrease the error of the angles, it is suggested to use quaternions instead of Euler angles.

I. Introduction

Resistance training in a gym is becoming more popular in all age categories. According the European Health & Fitness market report of 2019 [1], there was a 3.8 percent increase of health and fitness club members in 2019. Resistance training can also be described as weightlifting, where a person moves one or several body parts in a specific motion while having resistance with a certain amount of repetitions. Weightlifting could be done by body weight, machines, free weights or elastic bands. The goal of resistance training could be to lose weight, improve strength, gain mass or even improve mental health. People who just start going to the gym, need to inform themselves through the internet or they could hire a personal trainer. Due to the increase of inexperienced weightlifters there is an increase of need in personal trainers. However personal trainers can be expensive.

Making the accessibility of such a coach easier, could be done by making a coaching session shorter and more efficient. Looking at the main activity of a personal trainer, which is observing what a customer is doing, there could be an alternative way to observe and generate feedback. To make the observing more efficient a personal trainer could use technology that observes the motion and collects data on the performance of a training. It could even take over the generation of feedback, such that the AI coaches the weightlifter automatically. This option makes it available to help clients from a distance, and help more clients as well. Decreasing the contact time and thus the costs of a personal trainer. Such a device should measure all the metrics of the exercise in such a way that the application could detect when a user is performing the exercise correct or incorrect. The data obtained can then be used to give feedback and improve the performance. Metrics that should be measured are for instance the speed of the movement, the orientation of the limbs or the detection of which muscles are used to perform the exercise.

The use of IMUs can detect those motions. However, the use of those sensors in such an application give rise to certain research questions. The goal of this research is to determine the quality metrics of resistance training. Moreover an analysis is done for testing to what extent the data of inertial measurement units could detect those metrics, and what the quality is of this detection. The IMUs that are used are the NGIMU sensors of the company X-io Technologies, as those were available in the research group. The data collected is analyzed using MATLAB.

At the end of the project I have developed a framework that can be used to identify the incorrect body motions while performing certain exercises. The process chain will be validated using a test setup. The proof of concept could be extended to cover more exercises in resistance training, such that an end product could be created where personal trainers can analyze the performance of their clients from a distance.

II. Backgrounds

In order to understand the field of application, proposed methods and obtained results, various topics need to be elaborated. Therefore this section is used to explain the resistance training method, the use of IMUs, the software program Matlab and the optical measurement software Kinovea.

A. Resistance training

As already mentioned in the introduction, resistance training or weightlifting is done by moving one or several body parts. While moving a certain force is applied which causes resistance against contracting the muscles.

In weightlifting there are many different exercises a person can perform. The four main exercises are the bench press, pull ups, deadlift and the squat. A brief explanation of those exercises is given below [2].

1) Bench press

First of all the bench press, this exercise is used to train the chest and triceps. The person lays down with the face upwards, while holding a barbell with stretched arms. This is the start position. The repetitions exist of moving the barbell down, towards your chest in approximately two seconds and push it back up to the start position in approximately one second. In the lowest position the weightlifter should have the upper arms on an angle of 90 degrees with the upper body.

2) Pull ups

Secondly the pull ups, this exercise is used to train the back and biceps. The motion is done by hanging with stretched arms on a bar, this is the start position. Then you need to pull yourself up in approximately one second by having the focus that your elbows go downward. Next you go back to the start position in generally two seconds.

3) Deadlift

Third is the deadlift, which is done to train the lower back, glutes and hamstrings. To perform a deadlift, the weightlifter lays down a barbell on the ground and lifts it to a standing position in roughly one second. The upward motion should be done by having a straight back, while using about 80 percent of the strength from the legs and 20 percent from the lower back. After being in the upright standing position, the weightlifter needs to go down again in approximately two seconds until the barbell touches the ground.

4) Squats

The last exercise which is going to be explained is the back squat, hereinafter referred to as ”squat”, which is shown in Figure 1. To perform a squat the weightlifter holds a barbell on the lower part of the neck, while going from a standing position down in roughly two seconds, until approximately an angle of 90 degrees at the knees is obtained. Afterward the weightlifter goes back to the start position in about one second.

B. Inertial measurement units

To detect incorrect and correct motions of exercises in resistance training, it is chosen to use inertial measurement units. As IMUs are relative cheap sensors to use. Furthermore the method of extracting the data from the sensors is relatively easy, compared to methods such as visual detection by the use of cameras.

For this research NGIMU sensors, of the company x-io Technologies [3] are used. The placement of the IMUs is discussed in the data collection section, which is depended on the properties of a correct squat, mentioned in the section ”squat analysis”. Using IMUs will provide information such as acceleration and angluar velocities. In this research the orientation output data of the sensors is used, which uses the integrated accelerometer, gyroscope and magnetometer with an on-board AHRS fusion algorithm. The orientation data of the IMUs are in the form of quaternions [4]. Which is a four dimensional vector $q = cos(w/2) + sin(w/2)(xi + yj + zk)$. Where w indicates a rotation around the vector [x y z]. It is chosen to convert the quaternions to the euler angles roll, pitch and yaw. Euler angles are simpler to interpret and imagine regarding to the limb orientations. Furthermore the data will also be used by personal trainers, who are in general not familiar with quarternions.

C. Software

The goal of this research is to create a framework where incorrect body motions during resistance training can be detected such that feedback can be generated. The framework is designed using the software Matlab, where it is able to design applications and execute mathematical algorithms.

For this research the choice is made to analyze the data offline. X-io technologies supplies software to log all the sensor data via a WiFi router and save it on the computer. It is optional to log the data real-time, but for the creation of the framework this is not necessary and could even delay the design process.

Furthermore, to confirm that the algorithm created in Matlab is correct, optical measurements are done to compare the results. The software used for the optical measurements is called ”Kinovea”. The program can measure angles, lengths and movement speed, using video recordings and pictures. An example of such a measurement is given in figure 10.

III. Methods

The creation of the proposed framework is done by a couple of processes, which will be discussed in this section. First two personal trainers and one physiotherapist are interviewed. Next a detailed analysis of the squat is discussed. Furthermore the method of collecting the data is explained. To use the framework, a simple GUI is designed. The final part of the method consists of the designed data processing chain and the validation method.

A. Consultations

To get a better overview of the main exercises explained in the background section, two personal trainers and a physiotherapist are interviewed. One personal trainer has experience for 10 years, and the other for one year. Both did a study in sports, called the ALO, which is a study for teaching in physical education. The physiotherapist is specialised in sports physiotherapy.

During the consultations, which were in the form of semi structured interview, questions were asked regarding the correct motion and correct posture of the main exercises and the importance of those exercises during training sessions. The answers were noted during the interview in a digital document. The elaborate notes of the three interviews is given in the appendix.

From the information obtained, it can be concluded that the squat exercise is done by almost all the levels of weightlifters, as it has many benefits such as increasing strength in the lower body and the body core. Furthermore it increases endurance and helps significantly for fat loss, as the exercise uses the largest muscle groups. However the squat is a relatively difficult exercise, compared to the others, such as bench press. This comes from the fact that the squat uses many body parts to perform the motion, such as the lower legs, upper legs, knee joints, lower and upper back and even the head. Because of the rather difficult motion and the outcome of the consultations, it is chosen to create a proof of concept based on the squat exercise, as the framework will be most useful for such an exercise.

B. Squat analysis

1) Correct squat properties

To obtain a clear view of all the metrics of a squat, this section is dedicated for a detailed analysis about the squat, such that the important metrics can be determined for creating the framework. The squat is explained in specific properties. Those properties are extracted from the research of Czaprowoski et al. [5], the research of Myer et al. [6]. and the interviews. Those metrics are listed and explained below. Furthermore the definitions of the spine are given in Figure 2.

Fig. 1: The back squat in the start and lowest position [7].

1) The feet need to be at shoulder width and parallel or at a maximum of 7-10 degrees outward. Furthermore the heels should stay on the ground the whole exercise.
2) The knee joints are in a straight line with the hips and feet. When the feet are slightly outward, the knee joints follow the direction of the toes.
3) The hip joints should be bend and shifted backwards.
4) While doing the squat the lumbar vertebrae should be kept in neutral position or a bit straightened.
5) The thoracic kyphosis needs to be kept in a neutral position or slightly straightened as well. However definitely not bend.
6) According to the research of Myer et al. [6], the trunk should follow the incline motion of the lower legs during the complete squat motion.
7) The head should be in a neutral position or slightly looking up such that the cervical lordodis is in line with the upper back.
8) The depth of the squat should be that the upper legs are parallel to the floor. At this depth, the knee joints make an angle of maximum 115-125 degrees. However the optimal depth is where the angle of the knee joints are approximately 90 degrees. Going lower will bend the Lumbar vertebrae too much.
9) The final property of a correct squat is the timing. In general the downward motion takes two seconds and the upward motion one second. There are variations of this property, but during the research it is decided to keep this timing as a reference, as it is most general in weightlifting.

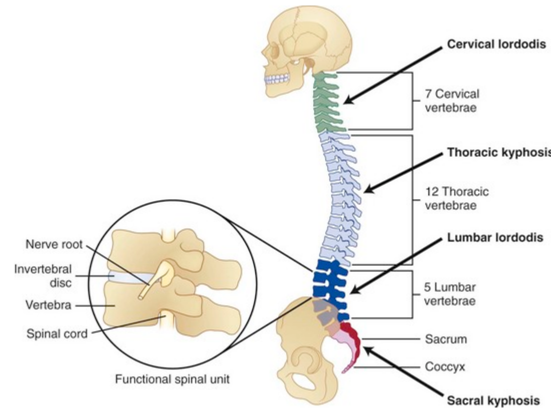


Fig. 2: Definitions of the different parts of the spine [8].

2) Squat mistakes

Looking at the properties of the correct squat, it can be seen that a significant amount of body parts are taken into account. This could make a correct motion technically difficult, as many things can go wrong. The most common mistakes are listed below. The effect of the incorrect motions is explained in the research of Czaprowoski et al. [5].

- The feet are set outside shoulder width.
- During the squat the heels are raised, causing them to be not in contact with the floor.
- The knees are pushed inward or outward, such that they are not in line with the hips and feet.
- The knee joints are going to far over the toes.
- Starting the squat motion by moving the knee joints forward first.
- Going too low, such that the knee joints make an angle more than 90 degrees.
- The lumbar lordodis gets bend, caused by backward inclination of the pelvis.
- The thoracic kyphosis is not in a neutral or straight position.
- The trunk is not kept at a constant angle during the squat, as the weightlifter lacks the control and stability of the lower back.
- The neck is not in neutral position, as the person looks too much up or down.
- The motion is made too fast or slow, such that the downward motion is not two seconds and/or the upward motion is not one second.

C. Data collection

To detect a correct squat and the mistakes discussed in the section above, sensors need to be put on specific body parts, see also Figure 4a. The decisions of the placements is explained below. Where the placement of the IMUs is directly connected to the specified properties of a correct squat. Concluding from this information, it is needed to use 10 IMUs. The placement can be seen in Figure 3.

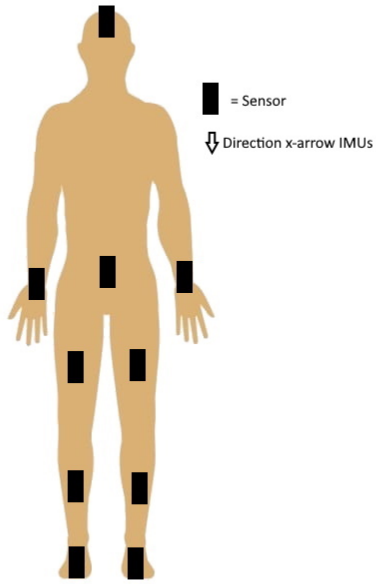
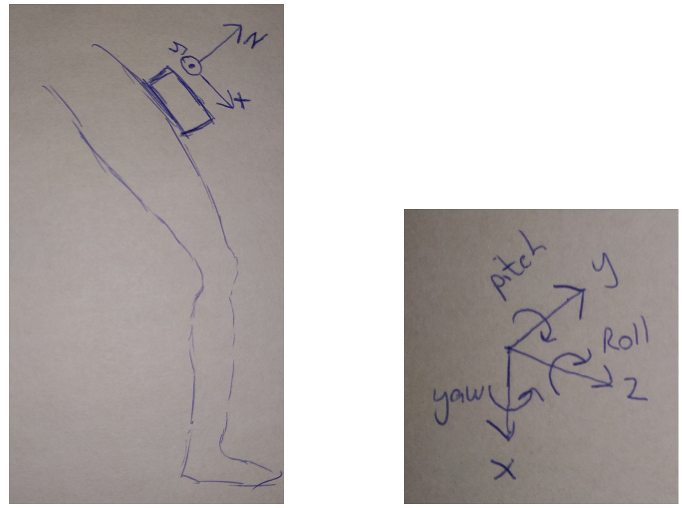


Fig. 3: Positions of IMUs on the body [9].

- The first sensor is put on the head, to detect the posture of the cervical lordodis, see property 7.
- Secondly there are sensors on the wrists, to detect the orientation of the trunk. As the hands are fixed at the barbell, the trunk and hands have a rigid connection. See properties 4, 5 and 6.
- Next there is a sensor on the hip, exactly below the belly button. Together with the wrists sensors those IMUs can determine the angle made by the lumbar lordodis and thoracic kyphosis. See properties 4 and 5.
- There are sensors on the upper legs, to detect how large the range of motion is and the inward or outward motion of the knee joints. Furthermore those sensors can detect the timing of the down and upward motion. See properties 2, 8 and 9
- The sensors of the lower legs are combined with the upper legs to detect the angle made by the knee joints. Moreover they are needed to detect if the trunk is not exceeding the incline orientation of the lower legs. See properties 6 and 8.
- The last two sensors are put on the feet, to detect if the heels are kept on the ground the whole squat. See property 1.

1) Calibration

To calibrate the sensors the start position of the squat is used. As this is a calibration with only one static position and no dynamic movements, it is assumed that the sensors are lined up the same, and the x arrow direction is straight down, while being in the start position. A representation of the IMU orientation is shown in Figure 4a. If this assumption is not met, the calibration method needs an additional dynamic movement, such as a squat motion. However it is chosen to exclude this and prevent errors with the alignment.



(a) Orientation of IMU on the leg.

(b) Representation of Euler angles.

Fig. 4: IMU orientation

After pressing the start button of the data logger, provided by the company of the sensors, the timer starts. The weightlifter needs to be in the calibration position before the timer is at 10 seconds and stay in this position until the timer reaches 15 seconds. Next the squats can be performed. A more elaborate measurement protocol is available in the appendix.

The squat analysis is based on the orientation of the limbs with respect to the start position. To have the start position as the zero point, the following process is done by the algorithm. The framework uses the data between the 11th until the 14th second of the recording to obtain the average values. The average will be subtracted from all the samples such that the start position gives zero pitch, roll and yaw.

2) Data set

To design and validate the application, measurements are done. The data set consists of one time six repetitions of a correct squat. Furthermore for every mistake mentioned in the squat analysis section five repetitions are measured and recorded. All the measurements are done by one person, due to limitations of COVID-19.

D. Data processing

The designing of the data process chain is based on iterations of the properties list of the squat. The calibration and conversion is shown in Figure 5. In the coming subsections there will be an explanation of the data processing per chosen property. The end framework will combine all those processes in the simple to use GUI. Furthermore, the analysis of the squat motion is based on the pitch, roll and yaw angles of all the individual IMU sensors. Due to time constraints, only three properties from the list in the squat analysis are covered in this research. The decision of the chosen properties is based on the frequency of the mistakes.

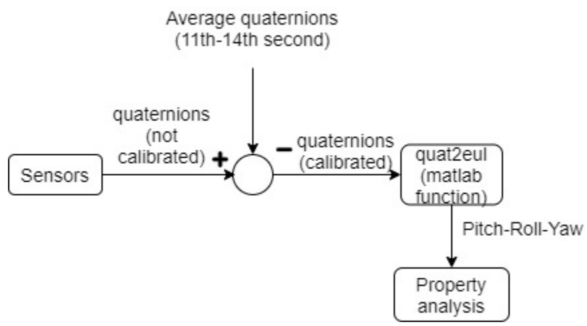


Fig. 5: Data processing chart

1) Motion speed

The first property chosen is the speed of the motion. Performing a squat too slow, which is below the 2 seconds down and 1 second up, can indicate that the weightlifter uses too much weight. This is dangerous for injuries. Moreover, performing the motion too fast can indicate that not enough weight is used. However if enough weight is used, but the motion is executed too fast, it could also lead to injuries.

To determine the timing of a repetition the pitch values of the upper legs are used. During the downward motion, the pitch angle increases to a value relative to the start position, with approximately a maximum value of 90 degrees. During the upward motion the angle will go back to zero degrees. The shape of the graph will be a parabola. The timing of the downward motion is indicated by the difference of the start and peak of the parabola. Furthermore the upward motion is the difference between the peak and end of the parabola.

The start time and end time of the parabola is determined by the matlab function: 'findchangepts(signal, 'statistics', 'rms', MaxNumChanges',2)'. The function searches in the plot the two points where the root mean square of the signal changes most significantly.

For determining the peak time, the 'findpeaks(signal,'MinPeakDistance', 1)' function is used, where the minimal peak distance is set to 1 sample. The function will indicate where local maxima are located. To remove the local maxima outside the parabola, an if statement is used, such that it checks if the location of the peak is between the two values from the findchangepts function.

The downward time is calculated by subtracting the start time from the peak time. The upward time is calculated by subtracting the peak time from the end time. This is done for both legs. The time presented in the GUI in Figure 7 is the average timing of both legs.

2) Angle of the trunk

The second property which is analysed by the application is the angle made by the trunk. As a incorrect posture of the trunk can lead to significant back injuries.

According to the research of Myer et al. [6], it is stated that the trunk should follow approximately the pitch angle of the lower legs. To check this property the pitch of the trunk and average pitch of the lower legs is compared. Then the maximum difference is presented in Figure 7.

3) Knee joint angle

The last property which is analysed by the algorithm is the angle made by the knees. The goal is to have a maximum angle of approximately 90 degrees. However starting weightlifters could deviate more than 10 degrees from this. Which could result in knee joint injuries.

To determine the angle made by the knee joints, the pitch values of the upper and lower legs are used. As mentioned before, it is assumed that the sensors of the lower and upper legs are exactly aligned. So according to the research of Liu et al. [10], the sensors can be put virtually on top of each other, as can be seen in the figure 6. This enables the determining of the angle of the knee joint in the sagittal plane by, adding the pitch values of the upper and lower leg.

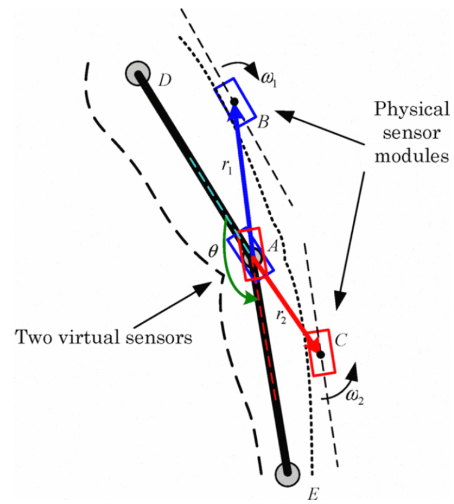


Fig. 6: Determining angle of knee joint by using virtual sensor placement [10]

E. GUI

To use the framework in a convenient way, a graphical interface is designed using Matlab app designer. To use the framework, the data should be put in the dedicated "measurement" folder. Then the initialize data button can be pressed. This will plot all the roll pitch and yaw graphs divided over several tab pages. The first screen is showed in Figure 7. To analyze a repetition, first the start and end of a window need to be given in the boxes on the right bottom. Then cut button can be pressed. This will show the given window next to the whole set of repetitions. To check all the properties of the squat for this repetition, the check button needs to be pressed. This will display the needed values in the table on the left. Furthermore the plots used for the properties are displayed in the "check" tabs. The other screens of the GUI are given in the appendix.

F. Validation

To validate the processing chain, the performed squats are recorded, such that an optical analysis is done. During the squat the timer of the data logger is recorded in the background, to know the exact timing of the motion. To validate the angles, the software 'Kinovea' is used. In the program it is possible to track motions and analyze angles, when having a measured reference. Furthermore a wooden hinge is build, see figure 11, to validate the process of determining the knee angle.

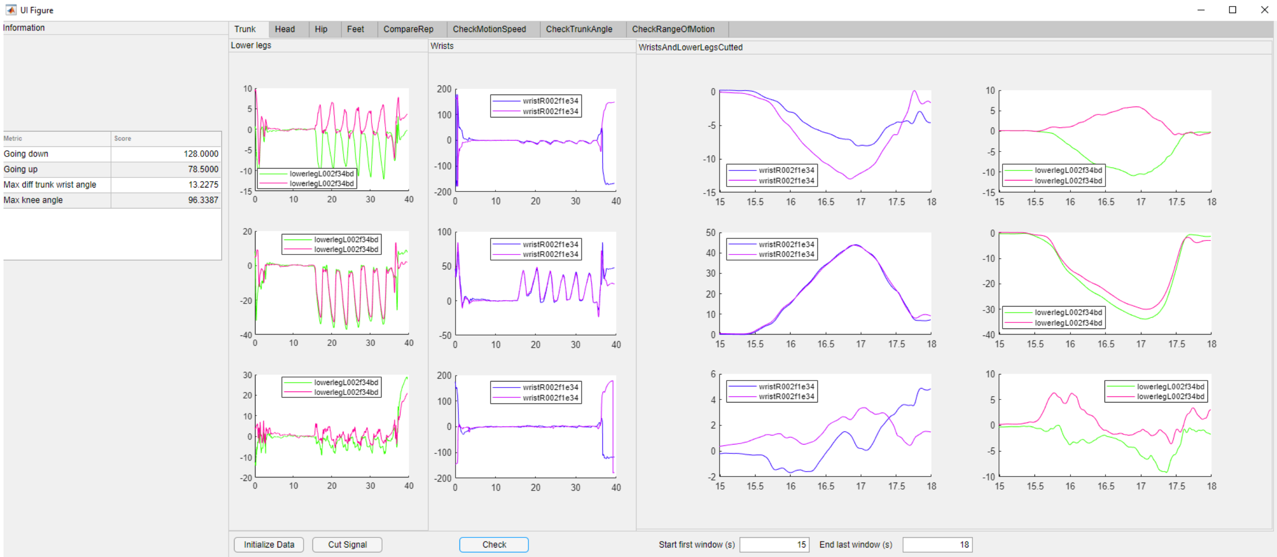
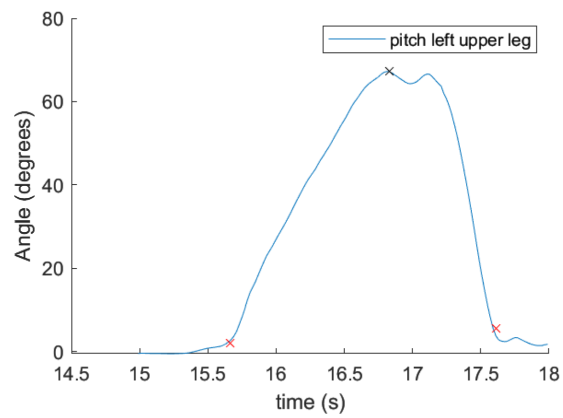


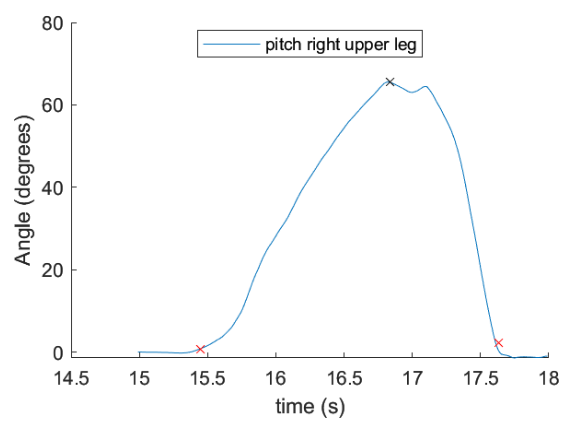
Fig. 7: First screen of the GUI, including plots of a squat.

IV. RESULTS

In this section the results are divided in the separate properties discussed in the method. Next to the individual results of only one repetition, an error analysis is done using the six repetitions of the correct squat. Moreover results are shown, where on purpose mistakes are made according to the properties covered by the application.



(a) Left leg



(b) Right leg

Fig. 8: Plots to determine the timing of the squat motion.

A. Motion speed

The first result is the output of the speed check. The begin and end time of the squat is determined by the algorithm and indicated by the red crosses in figure 8a and 8b. Where for the left leg, the times are 15.66 and 17.61 seconds. For the right leg the times are 15.45 and 17.63 seconds. The black crosses indicate roughly the lowest position of the squat, however there are two maxima with a local minimum in between. The left leg has the cross at 16.83 seconds and the right leg has the cross at 16.84 seconds. Taking the average of both legs gives a time value for going down of 1.28 seconds. The upward motion is done in 0.79 seconds. Those values are determined by the algorithm, for this specific repetition. To validate the values, the squat is recorded with the stopwatch of the data logger in the background. Screenshots of the start, middle and end are in the appendix. Analysing the video gave for the downward motion a time of 1.37 seconds and the upward motion a time of 0.68 seconds. The measurements of the other repetitions is in the error analysis section below.

B. Angle of the trunk

The next method which is applied to the same repetition is the difference in angle of the trunk with the lower legs. To check if the trunk does not have a difference in angle of more than 10 degrees, and causing the spine to bend. Which would cause high forces on the lower back. In Figure 9 the difference in angle is plotted. The difference in pitch at the lowest position of the squat has an angle of 13.2 degrees, according to the algorithm.

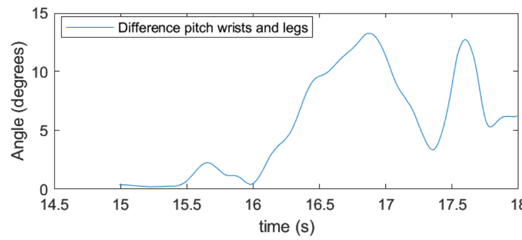


Fig. 9: Plot of difference in pitch between trunk and lower legs.

To validate if the algorithm is accurate, an optical analysis is done by the software Kinovea. The result is shown in figure 10. The lower legs made an angle of 35 degrees, shown by the green lines. The trunk made an angle of 47 degrees, shown by the red lines. So the difference is 12 degrees. As the trunk angle is determined by the sensors on the wrists, also the orientations of the wrists are shown with the yellow lines. The start angle of the wrists is different compared to the start orientation of the trunk. However in the lowest position of the squat, the orientations of the trunk and wrists are the same. This shows that the wrists do not have a rigid connection with the trunk, which is in contradiction with the assumption made in the method section.

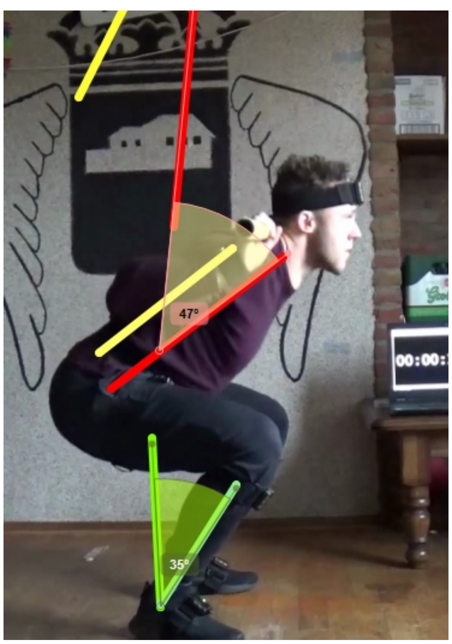


Fig. 10: Lowest squat position with angles made by the trunk and lower leg.

C. Knee joint angle

Before the angle of the knee is measured, a validation frame is used. This frame is made of wood and can be put in certain angles with one degree of freedom. The setup can be seen in figure 11. In the picture, the setup is exactly at 90 degrees at 21.4 seconds. The plot of going from "standing" position until 90 degrees, back to the start position is shown in Figure 12.

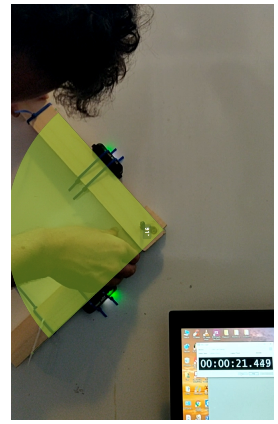


Fig. 11: Wooden knee angle validation setup.

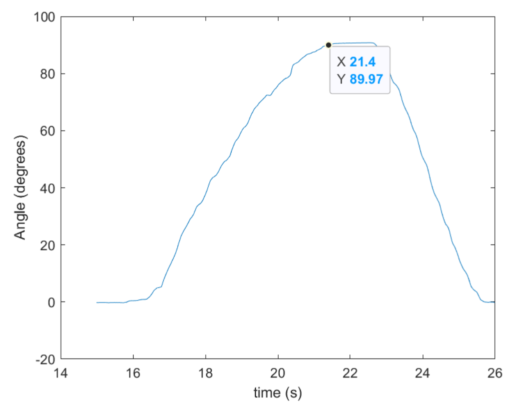


Fig. 12: Wooden knee angle validation setup at 90 degrees.

After the validation with the wooden frame, the method to determine the angle of the knee joint is applied to the same squat repetition as before. Where the average pitch of the upper legs and average pitch of the lower legs are added. This addition is plotted and seen in figure 13. The angle of the knees in the lowest position of the squat is 95 degrees, according the algorithm.

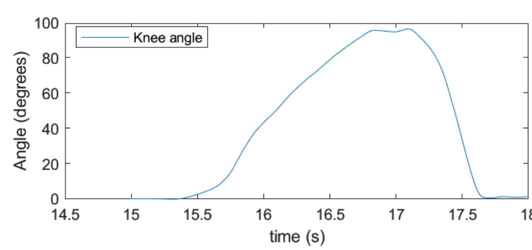


Fig. 13: Plot of the knee joint angle.

To validate the angle of the knee, the same optical validation like the trunk angle is done. The result is shown in figure 14. The angle made by the lower leg is 35 degrees. The angle made by the upper leg is 79 degrees. So the angle made by the knee is 114 degrees from the start position.

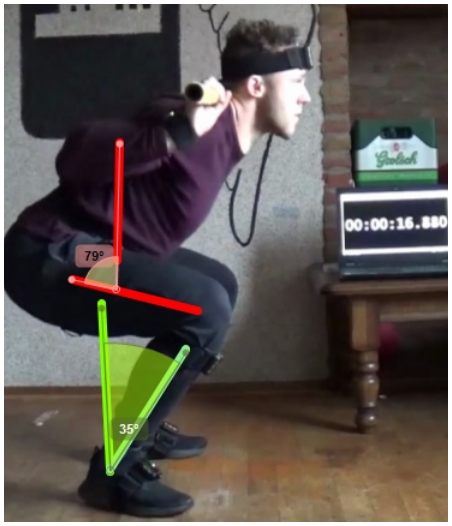


Fig. 14: Picture of the upper and lower leg angles.

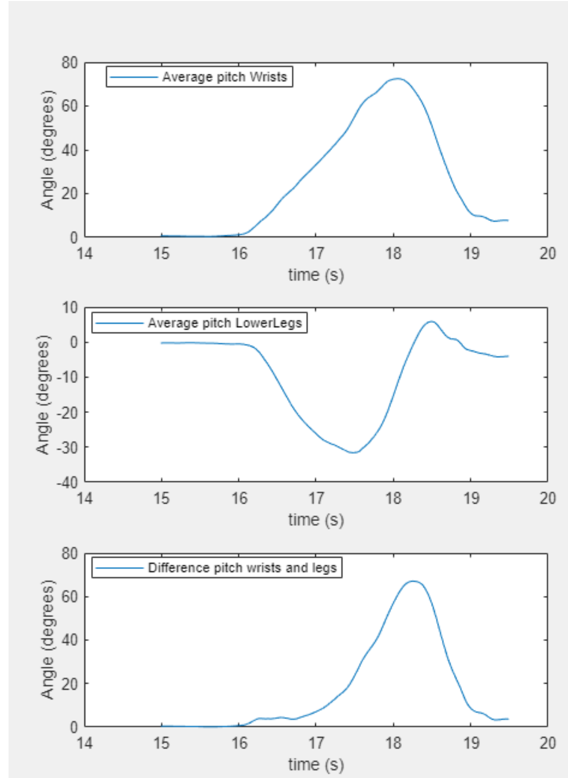


Fig. 16: plots of the pitch of the trunk, lower legs and its difference.

D. Mistake by the trunk angle

Regarding property 6 in the squat analysis, the trunk angle should follow the angle of the lower legs. When the weight is too high, weightlifters tend to lack the upper body when going up to the start position, as the legs are stronger compared to the lower back. An illustration is shown in figure 15 and the corresponding plots in figure 16. The difference in angle according the picture is 46 degrees. The difference in angle according the algorithm at the same time stamp is 41.57 degrees. Note that this is not the maximum difference, as that happens at the moment when the weightlifter was standing straight with his legs, but almost a 80 degrees angle at the hips. Furthermore it is important to know that the mistake is exaggerated.

Fig. 15: Squat where the upper body lacks behind while going up.

E. Squatting too deep

Regarding to property 8 of the squat analysis, the squat should be made until approximately a knee angle of 90 degrees is achieved. When a higher angle is made, as shown in figure 17 and the corresponding plot in figure 18, the lower back starts to bend, which is called a "buttwing", this could cause injuries. Furthermore too much stress is forced on the knee joints, which also creates a higher chance of injuries. Regarding the optical measurement the knee angle is 135 degrees. However regarding the algorithm plot, the angle of the knee joint is 110 degrees.

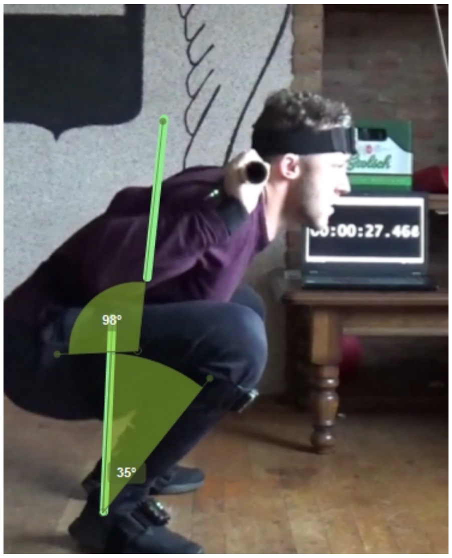


Fig. 17: Squat where the angle of the knee joint is 135 degrees.

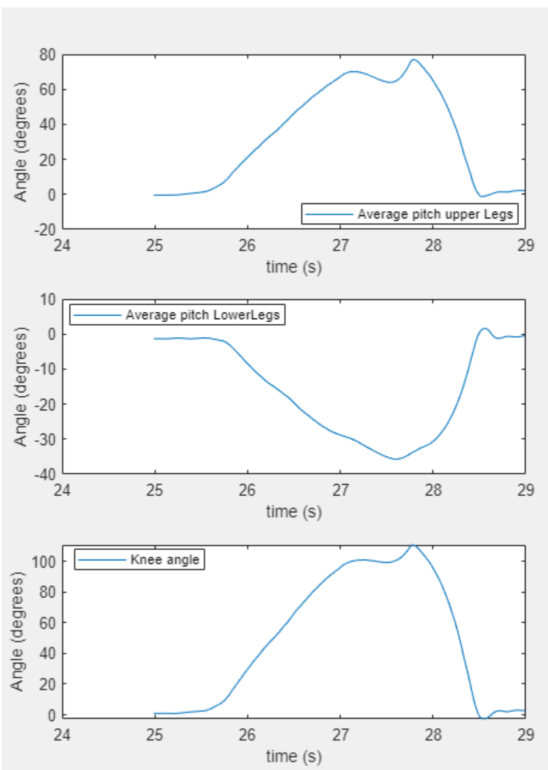


Fig. 18: Plot where the angle of the knee joint is 110 degrees.

F. Error analysis

In the error analysis, the algorithm values are checked, by doing the measurements manually as explained at the section of the validation method. The values of the algorithm are subtracted from the manual measurements. The results are shown in the tables below.

1) Correct squat

To be able to conclude on the general performance of the algorithm, six correct squat repetitions are analysed, see figure 19, using the method described above. The results are expressed in errors, which is the difference between the optical measurement minus the value the application determined. The optical measurements of the timing have an accuracy of 0.04 second, caused by the frame rate. The optical measurements of the angle can deviate plus or minus 5 degrees.

Rep	Downtime Error	Uptime Error	TrunkAngle DiffError	KneeJoint AngleError
1	0,22	0,01	-1,23	17,66
2	0,05	0,19	2,9	14,74
3	0,07	0,22	3,82	19,42
4	-0,01	0,29	5,7	20,338
5	-0,03	0,32	9,88	20,42
6	-0,1	0,33	11,63	22,03
Average Error	0,033333333	0,226666667	5,45	19,10133333
Standard Deviation	0,10966616	0,119777572	4,725708413	2,570818287

Fig. 19: Error analysis of 6 correct squats

2) Mistake by the trunk angle

Regarding the result section about the mistake of trunk angle, an error analysis is done with 5 repetitions. The maximum difference between the lower legs and the trunk is measured via Kinovea and compared to the application. See the results in figure 20.

Rep	TrunkAngle DiffApp	TrunkAngle DiffOptical		TrunkAngle DiffError
1	67,08	69		1,92
2	37,03	46		8,97
3	59,5	62		2,5
4	55,12	60		4,88
5	70	73		3
			Average Error	4,254
			Standard Deviation	2,860468493

Fig. 20: Error analysis of 5 incorrect trunk angle squats

The average error between the application and the optical measurement is 4.3 degrees, whereas the standard deviation is 2.9 degrees.

3) Squatting too deep

The last error analysis is done for 5 repetitions where the squat is made too deep. The results are shown in figure 21

Rep	KneeJoint AngleApp	KneeJoint AngleOptical		KneeJoint AngleError
1	106	131		25
2	102,5	133		30,5
3	110,67	134		23,33
4	109,73	131		21,27
5	107,7	119		11,3
			Average Error	22,28
			Standard Deviation	7,029398979

Fig. 21: Error analysis of 5 incorrect too deep squats

In the figure it is shown that the average error is 22.28 degrees and the standard deviation is 7.03 degrees.

V. Discussion

In this section a critical look is taken on the obtained results. To keep a clear overview, the discussion is divided in the same sections as the results.

A. Motion speed

Looking at figure 19, the following can be discussed. For the down motion, the average error is 0.03 seconds and has a standard deviation of 0.11 seconds. For the upward motion, the average error is 0.23 seconds and it has a standard deviation of 0.12 seconds. As the upward motion should be done in approximately one second, deviation of at least 0.1 second should be visible by the algorithm, to significantly sense incorrect timing. Regarding the standard deviation of the algorithm, this is not achieved. The first two causes are seen in figures 8a and 8b. The start and end crosses are not exactly at the start and end of the parabola. This could be caused by the fact that the angle of the upper leg is not changing significantly enough to detect the start and end that accurate. The rate of change at the start and end is approximately 1.5 degrees per 0.5 second.

Furthermore the plot has a 'bump' of 2.9 degrees at the top, resulting in two peaks. This causes the algorithm to deviate plus or minus 0.1 second from the lowest position of the squat, which is exactly in the middle of the 'bump', regarding the optical measurement. This drop could be caused by four problems. First of all due to the thick training tracksuit bottoms, which dents. Secondly, the relaxation and contracting of the muscle causes the IMU to go up and down. The third problem can be detected by looking at the slow motion recording of the squat. The motion of the squat at the lowest position, only includes absolute movement of the upper leg IMUs, where the lower legs still tilt forward. This combination of motions move the upper legs 3 degrees up again. The last possible cause could be that the conversion method from quarternions to Euler angles can not convert correct when the quarternions go beyond 90 degrees. Which could be solved by not converting the data.

A solution to determine the peak more accurate could be by using the acceleration data of the sensors. A plot of one repetition is shown in figure 22.

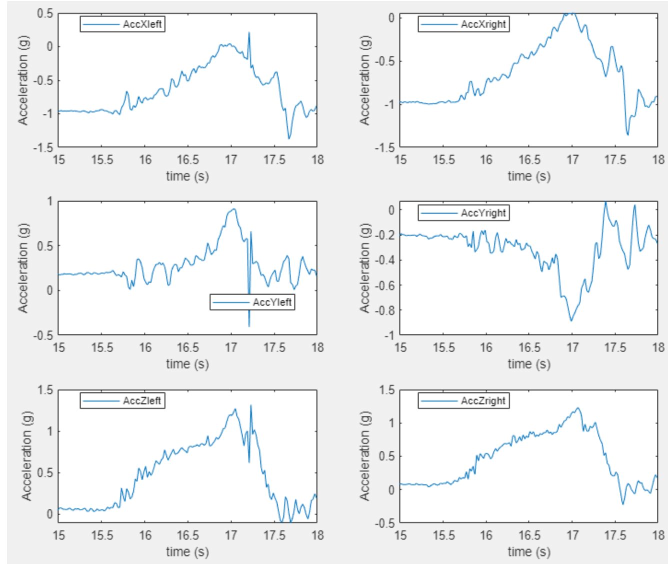


Fig. 22: Plot of the acceleration data of the left and right upper leg.

The weightlifter was in the lowest position exactly at 17 seconds. This is in the plots exactly represented at the peaks. Using this graph after a low pass filter and a specific threshold to sense the peak, would increase the accuracy of determining the timing of the lowest squat position.

B. Angle of the trunk

The second result is the difference in the pitch angle of the trunk and the lower legs. The average error is 5.5 degrees, and has a standard deviation of 4.7 degrees. This could be caused by the accuracy of the optical measurements. Furthermore it can be seen by the yellow lines in figure 9, that the wrists make a smaller angle going from start until the lowest position compared to the trunk. This indicates that the wrists IMUs are not exactly representing the angle made by the trunk. Possible ways to solve this are discussed in the recommendation section.

C. Knee joint angle

The third result is obtained by values for the angle of the knee joints. Before a measurement on the body was analysed, the technique of adding the pitch values of the upper and lower legs was validated. This was done by using a wooden frame. Looking at figure 11 and 12, the angle obtained by the plot corresponds with the angle made by the wooden frame with a deviation of 2 degrees.

After the wooden frame validation, the data of the squat is used. Comparing the optical measurement with the algorithm, the average error is 19.1 degrees, with a standard deviation of 2.6 degrees. This is a significant error, but a relatively low standard deviation. Regarding the low standard deviation, the high error could be caused by the fact that the IMUs are not perfectly lined up causing a offset, which was not the case on the wooden frame. Furthermore the legs are not as straight as the wooden frame, as the legs have a slight curve on the surface, due to muscle and fat. The lack of sufficient calibration, such as including dynamic motions could cause the consistent error. However as mentioned in the discussion of the motion speed, the error is most possible from the fact that the Euler angles do not exceed a certain angle. Because of the conversion method.

D. Mistake by the trunk angle

Regarding the analysis of the mistake made by the angle of the trunk, we can see that the average error is 4 degrees, which could be caused by the accuracy of the optical measurement.

Furthermore it needs to be noted that the maximum difference is not always at the lowest position of the squat. As shown in the figures 15 and 16. When the maximum angle is after the lowest position, it can be concluded that the trunk is lacking behind in the upward motion. If the maximum angle is before the lowest position, it can be concluded that the trunk drops faster then the legs. Both mistakes could indicate that the weight is too high.

E. Squatting too deep

Looking at the error analysis in figure 21, where the squat is performed 5 times too deep, the average error is high, whereas the standard deviation is lower. The cause of the consistent error, could be again because the conversion to Euler angles can not go beyond a certain degree. When the squat is too deep, the upper legs travel a significant higher angle then 90 degrees.

VI. Conclusion

To conclude, the goal of the research was to develop a framework that can be used to identify the incorrect body motions while performing certain exercises. Looking at the results, the goal to determine the quality matrices of a squat is reached. However the application can't detect the timing of the squat accurate enough, as it has an average error of 0.2 seconds. Furthermore the trunk and knee angles are determined insufficiently by the algorithm. The determined values of the knee angle differs with an average error of 19 degrees with the optical measurement. The inaccuracies could cause the algorithm to generate incorrect feedback. However looking at the possible solutions for the inaccuracies, IMUs are sufficient to sense the quality matrices of a squat. The algorithm needs to be improved, with the proposed solutions.

A. Recommendations

In this section recommendations for future research are given. The recommendations are divided in changes in the current framework, and possible additions to it.

1) Changes in current framework

First of all, an improvement could be made with the determination of the upward and downward timing. As the squat causes the lower leg to not only move in an angle, but also absolute movement is present. It is recommended to use the acceleration data. This will provide a clear time point for the lowest position, as the acceleration and speed is zero at this point.

Secondly an improvement could be made at determining the angle of the trunk. It was assumed that the wrists have a rigid connection with the trunk. However this is not true, as the elbows are pushed slightly more backward in the start position compared to the lowest position. This results in a different angle trajectory of the wrists in comparison with the trunk. It is recommended to change the position of the IMUs to the upper back, at chest height.

The last improvement could be made for determining the knee angle. As mentioned in the discussion, with the current algorithm, Euler angles are used. However the conversion algorithm is limited to 90 degrees in the quaternions. So it is recommended to use quaternions.

2) Possible additions

Next to the improvements, more metrics of the squat should be included. Such that all the properties of the squat are analysed. Furthermore more exercises should be included, such that a complete workout can be analysed by the framework. Another possible addition could be the use of machine learning. Using all the metrics obtained from the exercises can function as input for the machine learning algorithm.

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APPENDIX A
INTERVIEWS

The interviews were held in a semi structered interview. However not all questions are asked to all the three professionals. The first interview with a personal trainer was done with more general questions, asking which exercises give most problems and are important to analyse. Based on the outcome the other two interviews are based on specific questions about the squat, benchpress and deadlift.

1) How many years are you personal trainer, and did you do a study for it?
   - 1 year personal trainer and did the ALO study.
   - 10 years personal trainer. Weightlifter for 15 years. Did the ALO study.
   - -
2) Which exercises give most problems/injuries for new weightlifters?
   - Most injuries are at the lower back, with squats and deadlifts. The weightlifters go too low, or have the barbell too much forward, so their back is bend. Furthermore a too low squat gives a butt swing, which also bends the lower back.
   - -
   - There are a lot of shoulder problems, as they have many degrees of freedom. They need a lot of stability. A lot of young weightlifters are too enthausiastic and obtain overloaded. Furthermore shoulder problems are caused often because of incorrect training.
3) What are the important properties of a squat?
   - Feet stay on the ground. You need to look forward and push your chest forward. Push the knees slightly outward. Feet need to stay on shoulder width. When a person lifts heavier, those properties go wrong more often.
   - The properties of a squat are
     - All moving parts.
     - How is the bone structure of a person
     - How is the anatomy?
     - Feet slightly outward
     - The wider the feet are on the ground, the more the feet need to point outward.
     - Knees need to follow the feet. You need to have the feeling that you turn your feet outward into the ground while performing a squat.
     - In the lower parts of the squat there is not much tension on the glutes. In the upper part, you use the glutes more.
     - Knees are allowed to go beyond the toes, if the flexibility is enough. You should not have all the weight on the front part of the feet.
     - For starting weightlifters prevent a buttwing.
     - keep the spine stable, through the whole motion.
     - Tilt the hip forward, such that you prevent bending the spine.
     - Push the shoulders backward.
     - You need to stabilize the upper body.
     - Keep looking forward, such that the spine stays in line.
     - Speed depends on the goal, but in general 2/3 seconds down and 1 second up.
   - For squats it is important to:
     - Don't let your knees go beyond the toes. The higher the knee angle, the more pressure there is on the kneecap. The knee angle should go approximately until 120 degrees. For revalidation this is important to consider. The knee joint is important as it also is connected to what muscle you train, the hamstring or quads.
     - Try to prevent the buttwing, however the buttwing is not connected directly to back problems.

  - Keep the weight on the heels.
  - With lunges the knee can go inward which is bad for the inner knee strap. This could also happen with squats.
  - Let the knee follow the ankle or even a bit more outward.
  - Young people get often injuries as they lift too heavy. They focus too much on the big muscles and have a incorrect motion.
  - Press the shoulder blades towards each other, this causes the back to stay straight.

4) What are the important properties of a benchpress?
   - -
   - The properties of a benchpress are:
     - Keep your arms 90 degrees with your body.
     - stabilize the shoulders. Push the shoulders down and forward but not to much.
     - The elbows can go slightly under the shoulder, to stabilize the shoulder, but not to far, as you will then use the triceps more.
     - Keep tension on the chest muscles.
     - Turn the inside of the hand inward when going up, this helps focusing of contracting the chest muscles.
     - Keep tension in the whole body. Have the feet on the ground and a little bit outward. Contract the glutes and core. When going downward, the lower back it is allowed to have a swayback.
   - The important metrics for benchpress are:
     - Keep the upper arms under the shoulder height. Or 90 degrees with the body.
     - Press the shoulders downward and forward.
     - Don't tilt the pelvis when pushing up, as this overloads the lower back.
     - Press the feet on the ground, for stability.
     - Don't lock the elbows in the upper position. This stretches them too much.
5) What are the important properties of a deadlift?
   - -
   - The propertie of a deadlift are
     - Bend your hips, such that it tilts forward.
     - Stabilize the back muscles, such that there is tension on the hamstrings.
     - Shoulders should be hold slightly backward, so don't let them fall forward.
     - The knees only make a small angle, to keep tension on the hamstrings.
     - Keep the head forward, such that the spine stays in one line.
   - The important metrics of the deadlift are:
     - New weightlifters should not use a lifting belt. When they think they need it, the weight is too much.
     - Keep the barbell as close to the body as possible.
     - Try to keep the knee angle as small as possible, depending on the flexibility of the hamstring. Keep tension on the hamstring and glutes.
     - Keep your head in line with the body.
     - Push the shoulder blades backward, if this is not possible, the weight is too much.

APPENDIX B
MEASUREMENT PROTOCOL

- Put all sensors on the assigned places.
- Start data logger on laptop.
- Stand in start position from the 10th until the 15th second.
- Do exercise.
- Stop data logger.

APPENDIX C
MEASUREMENT PICTURES

Fig. 23: Start position squat.

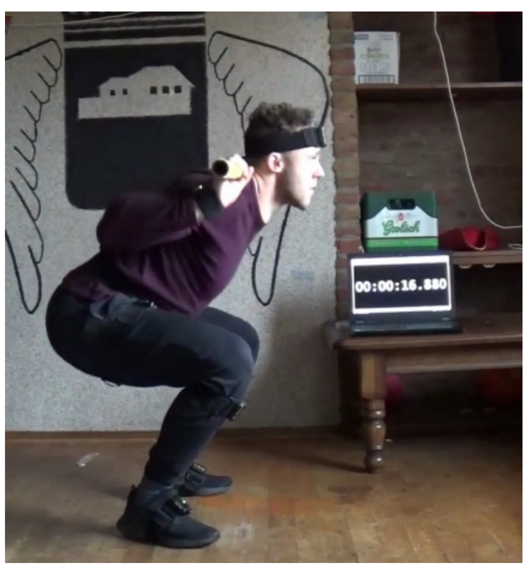

Fig. 24: Mid position squat.

Fig. 25: End position squat.

APPENDIX D
GUI

In this section printscreens of the application are given. Where a correct squat is analysed.

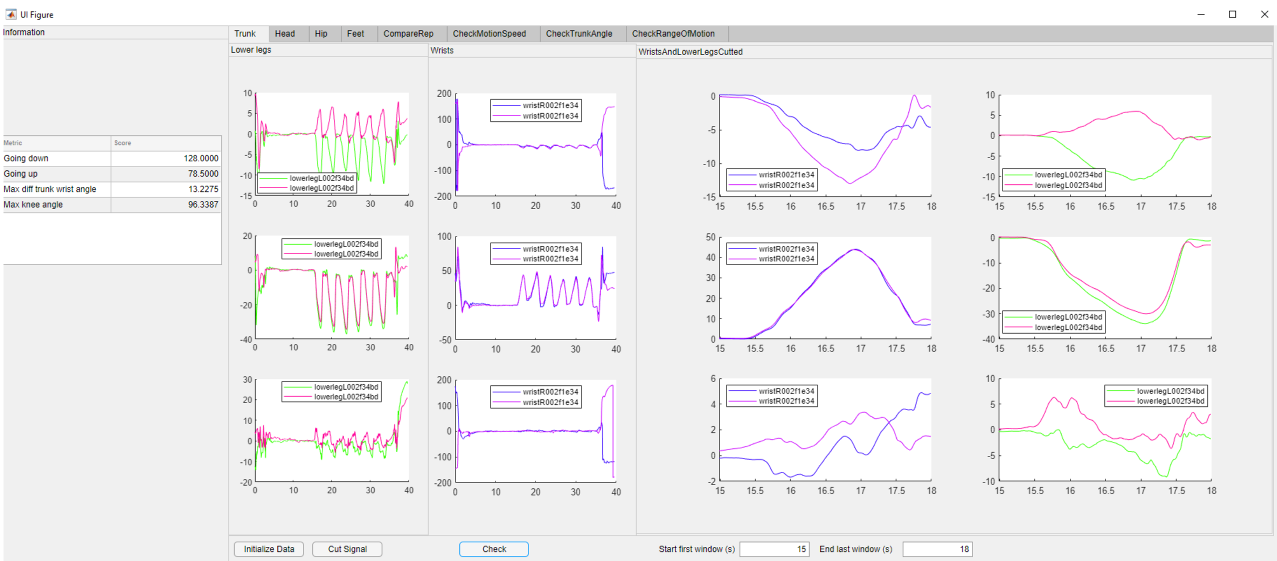

Fig. 26: First screen of the GUI, including plots of the lower legs and wrists.

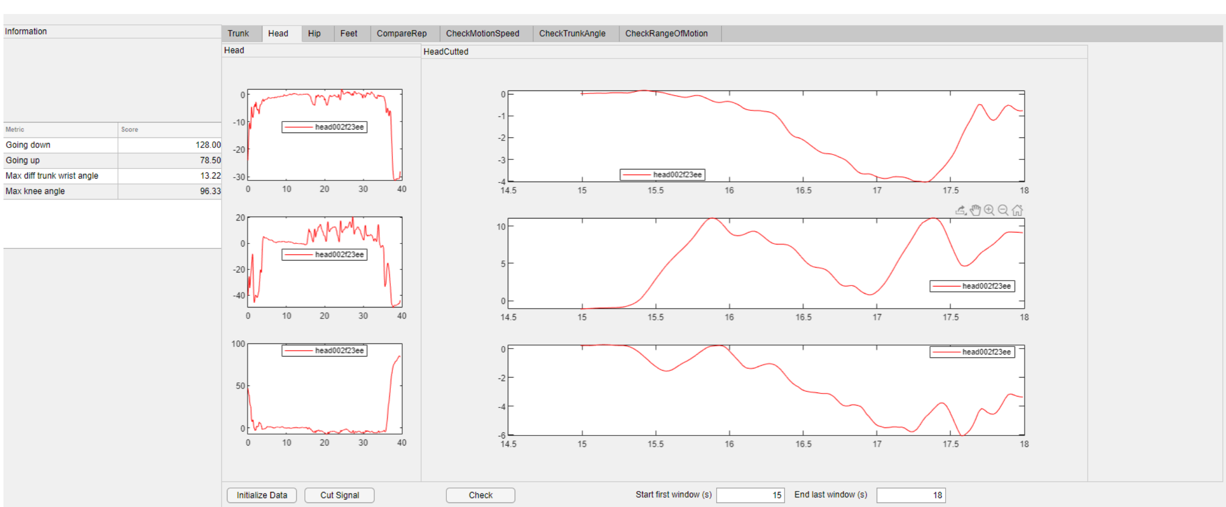

Fig. 27: Second screen of the GUI, including plots of the head.

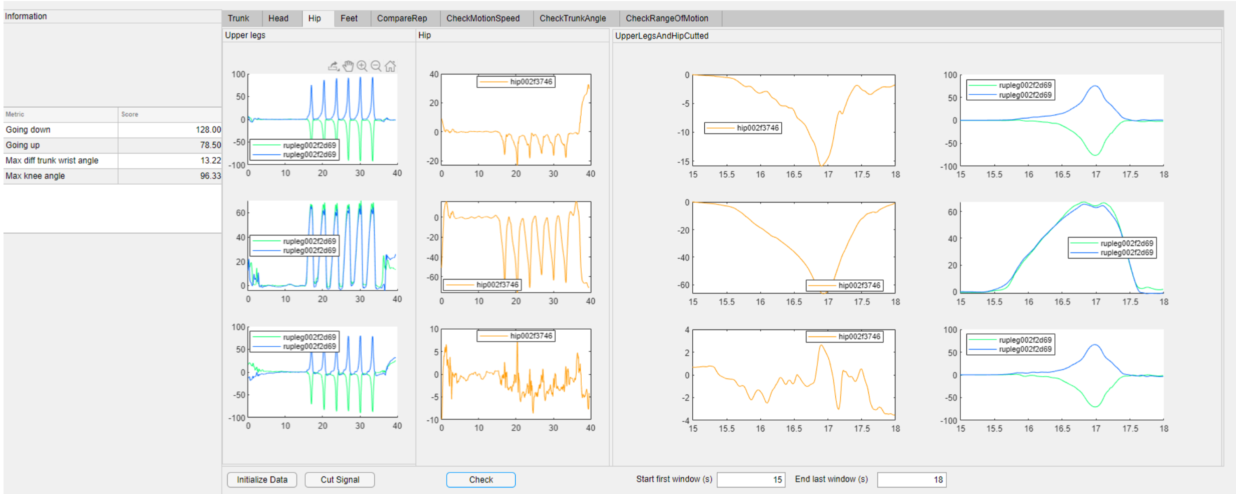

Fig. 28: Third screen of the GUI, including plots of the upper legs and hip.

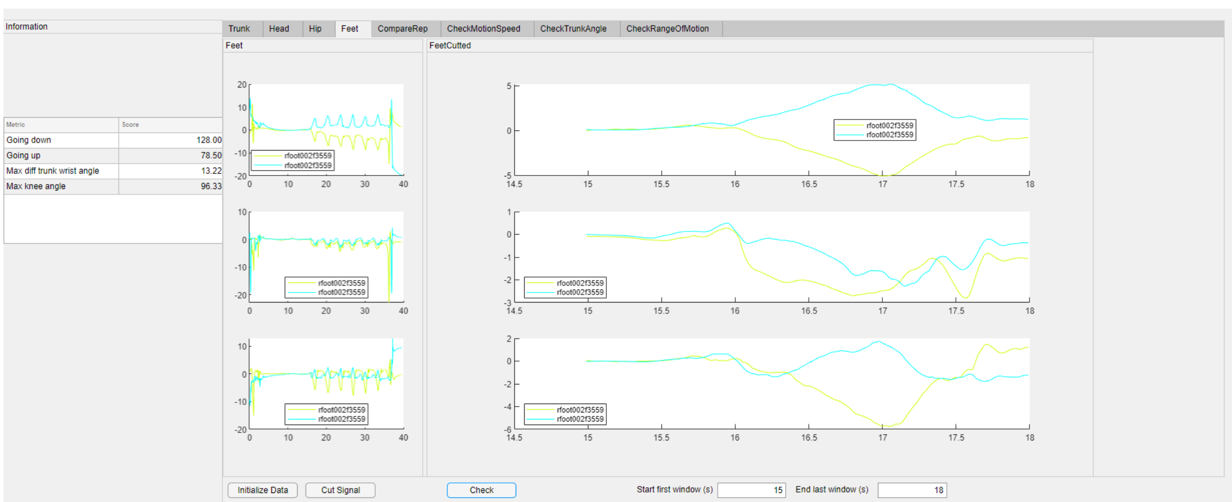

Fig. 29: Fourth screen of the GUI, including plots of the feet

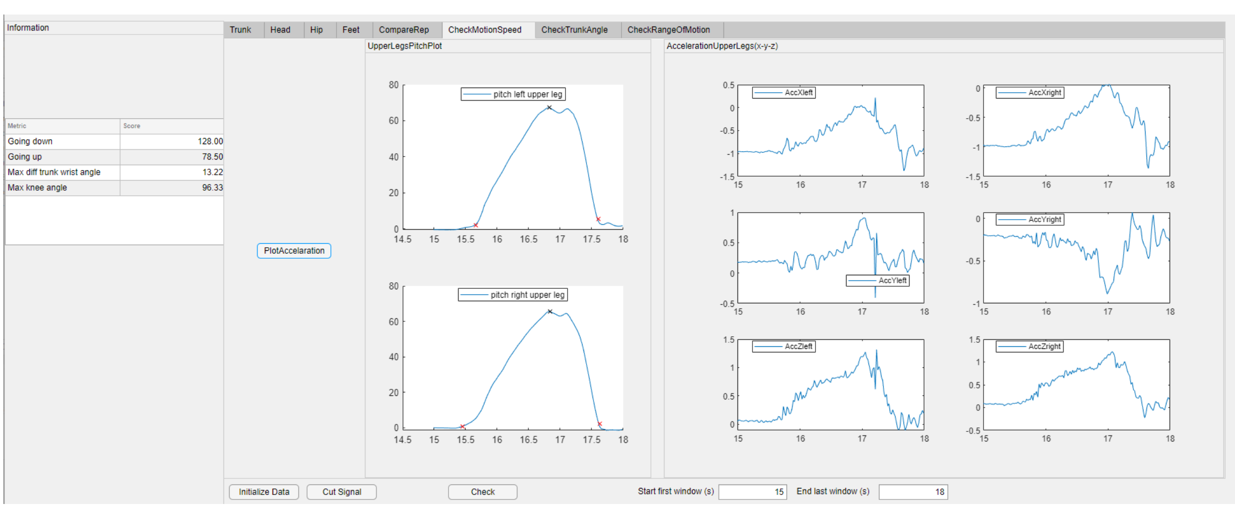

Fig. 30: Fifth screen of the GUI, including plots to check the timing of the squat.

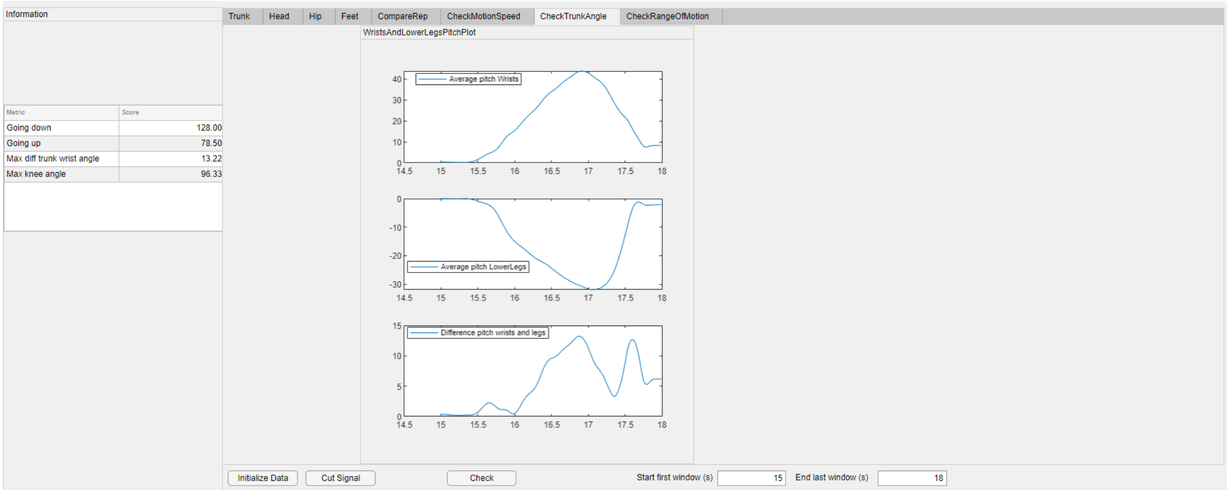

Fig. 31: Sixth screen of the GUI, including plots to check the difference in angle of the trunk and lower legs.

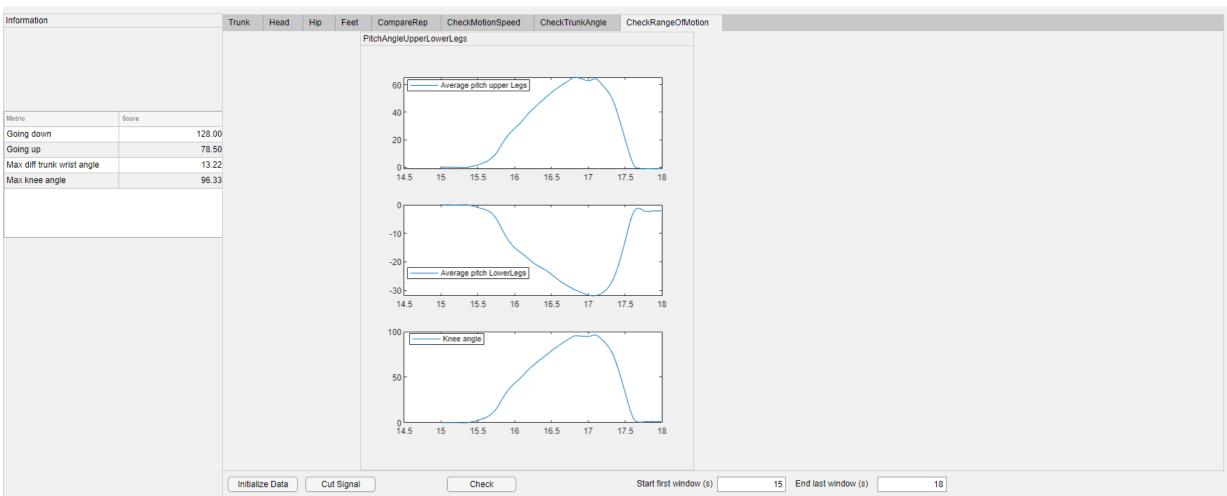

Fig. 32: Last screen of the GUI, including plots to check the knee angle.