Measurement shirt for the baseball pitch

Design paper: Design a shirt which combines measurements of the kinematic chain and muscle activity in order to know more about the cause of injuries in overhead sports.

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Abstract— **Pitching in baseball is a motion which is sensitive to injuries and it can lead to long lasting damage. Muscles in the elbow which are the most prone to injuries are the pronator teres and the extensor mass, both playing a large role in the stabilization of the elbow. A faulty order of movements in the kinematic chain is also a big cause for injuries in the sport. A shirt which combines inertial measurement units (IMU) and electromyography (EMG) sensors could give insight into detecting and preventing injury. The aim of this project is to build a useable and user friendly prototype of this shirt, fitted to a medium-sized junior player (16-18 years old). The most important criteria are the following: providing quality measurements of the IMU and EMG sensors, minimal interference with the pitching motion caused by the shirt and the ability to be washed and reused. To conclude the configuration using stretchable wiring between the IMUs and the EMG sensors to the central data collection device (hub) yielded the best results. The protection of the hub and IMUs are done by 3D printed casings, which are connected with velcro to the shirt. The result is a working prototype with comparable EMG measurements compared to the gold standard set in this project. The IMUs are working, but the range of the IMUs is exceeded by the peak values of the pitch.. However, the ball speed is not influenced by the shirt and the prototype is washable. Overall performance of the prototype meets the requirements.**

I. INTRODUCTION

It is unmistakable that in the sport of baseball a good pitcher is essential to defeat your opponent. Various pitching techniques have been developed to make it as difficult as possible for the batter. Ultimately, these techniques have proven to have a great impact on the body of the pitcher resulting in injuries in body parts such as the elbow and the shoulder [1]. At the moment, pitchers who get injured don't have a clear insight in what went wrong. So, in order to gain more information the causes of various injuries it is required that data is collected before the injury occurs. Therefore this report focuses on a young age group of 16-18 years old. To collect the information a device is needed which can conveniently gather the data of the pitching motion.

The need for a convenient calls for a portable solution with a minimal setup. Even though an optoelectronic motion capture system is the best solution for tracking movement, it comes with a lot of equipment and an elaborate setup. A sensor or combination of sensors like an inertial measurement unit (IMU) is a reliable method of tracking motion [2]. Electromyography (EMG) measurements are able to indicate muscle activity. Therefore a collection of sensors combined with a shirt can provide accurate results while still being convenient.

When it comes to clothing with embedded sensors, a sleeve has been developed which contains an IMU [3]. Measurements on pitchers have already been performed in the lab. A more elaborate description of what already has been done is given in the theory. The goal of this research is to use these sensors instead of a large set-up in a lab, which enables the user to take the measurements outside on the field and perform real time analysis during training and competition day without hindering the performance.

For this research the objective is to design a shirt which can measure the kinematic chain of the baseball pitch combined with the muscle activity of relevant muscles. The kinematic chain indicates the "combination of several joints linking several limb segments together during a specific movement or posture" [4]. Since this research is a design research, a design goal has been formulated accompanied by a list of requirements and wishes which are described in appendix A. The design goal is the following:
Design a shirt which combines measurements of the kinematic chain and muscle activity in order to know more about the cause of injuries in overhead sports.
In order to develop a shirt that meets the requirements the following steps are performed. To start off with the main components are separated and different concept solutions are designed. Secondly, the different components are reviewed individually to be able to determine the best solution. Finally, the best concepts for all main components are put together and the final prototype is made. This prototype is tested and evaluated. The paper is also structured in the way as described above, concluded with a conclusion and recommendations.

This design study is conducted by mechanical engineering students as part of the Bachelor End Project at the TU Delft in the third year of the Bachelor studies.

II. THEORY

In order to gain more insight into what causes the injuries these have to be linked to the motion and muscle activity of the pitching movement.

The most common locations where injuries occur are the elbow, shoulder, ulnar collateral ligament (UCL), rotator cuff, and superior labrum anterior posterior [5]. According to a study by Griffith, the amount of injuries to the UCL is increasing [6]. Aguinaldo points out that significant forces act upon the elbow which is a cause of injury for the UCL, flexor pronator, and the ulnar nerve [7]. Of all the baseball injuries, 8.2% is caused by an injury at the pronator teres. Furthermore 7.2% of the injuries is caused by an injury at the biceps and triceps [8]. Unfortunately, the injuries at these muscles are not further specified in the literature. This muscle group is also hard to measure because of its big displacements during the pitch. Finally, 2.3% of the injuries lie at the extensor mass [9]. To measure muscle activity, electromyography (EMG) or mechanomyography (MMG) can be used. When a muscle is in tension, electrical pulses run through it. EMG measures the difference in potential over the muscle. MMG is a relative new technology where acoustic signals from the body are measured. EMG has proven to be reliable and is the standard for measuring muscle activity nowadays, this is not the case for MMG, research suggest it provides similar results in some, but not all, cases [10][11]. EMG sensors have been used for measurements during the baseball pitch. Campbell et al. and Yamanouchi have measured activity in lower extremity muscles [12][13]. DiGiovine et al. have measured the upper extremities [14]. Jobe et al.have measured just the shoulder [15][16]. Because these studies have obtained usable results about the muscle activity during the baseball pitch, in this design study will also be made use of EMG sensors.

The kinematic chain between the relevant body segments also plays an important role in an effective baseball pitch. The relevant joints during the baseball pitch are the pelvis (hips), the thorax (upper body), the shoulder and the elbow. When they are used in the right sequence, the mechanical energy is able to flow conveniently through the movement. The most efficient transmission is reached if a body segment is initiated when the previous segment in the chain has reached its maximum rotational velocity [17]. As stated previously, several methods have been developed to analyze the motion of movement in sports and in particular in baseball. One example is motion capture technology which can capture the movement of a person using cameras and markings on the subject's body [18]. This can be a very accurate method but it requires an elaborate setup. The more portable IMU is a combination of an accelerometer and a gyroscope, sometimes in combination with a magnetometer [19]. While these sensors can be used separately it is advantageous to combine them into an IMU as this offers the possibility to increase accuracy [20]. This unit is used to measure the stature of the human body [21][22]. In prior work in baseball the IMU has been used in both the ball and the bat [23][24]. One of the main problems when using IMUs are the high angular velocities reached during the pitch. Youth and high school players reach an average maximum elbow extension velocity of around 2,200 °/s and an average maximum angular velocity of the shoulder of around 6,900 °/s. [25]. Lapinski et al. have placed the units on the athlete, these units make use of an enhanced gyroscope which is able to measure up to 11,000 °/s [26]. Unfortunately, this IMU is not yet commercially available and therefore not included in this design study.

Furthermore, it is important to recognize that injuries are not solely result of incorrect movement execution. As Hibberd et al. show, risk on elbow pain increases with 6% with every 10 pitches thrown, and exceeding 75 pitches, this increases to 50% [27]. Injuries can also be caused as a result of overtraining, so the shirt also has to provide feedback about the number of pitches performed.

III. METHODS

In order to achieve a first working prototype that satisfies all the requirements, the shirt is divided into four main components which are analyzed. The main components are: measurement of movement, measurement of muscle activity, wiring and data collection and processing.

A. *Measurement of the movement*

As described in the theory for this research an IMU is the most suitable way to measure movement. Its location and attachment to the shirt are discussed in the following parts. Four IMUs will be placed on the body to measure the four locations relevant to the kinematic chain: the pelvis (hips), the thorax (upper body), brachium (upper arm) and antebrachium (lower arm). Five types of IMUs are considered and compared in (appendix B). The 'TU IMU' is a customly assembled IMU, made using the most accurate gyroscope available and is the smallest option. Therefore, this type has been chosen.

IMU location

For the location of the IMUs three factors have to be taken into account. Firstly, to ensure accuracy the sensors have to be placed in the locations where the movement is the greatest during the pitch and where therefore the acceleration is the easiest to measure. Secondly, the IMUs also have to be placed in locations with minimal movement of the underlying muscles. Lastly, the IMUs should be placed in such a way that it is easy to connect the wiring. For the locations there will be referred to 1,2,3, and 4 in Fig. 3. The sensors for the upper and lower arm will be located at the wrist (4) and close to the elbow (3) (From now on called the wrist and elbow IMU respectively). This is where the movement is the greatest. The placement near the elbow will also avoid the bicep and tricep muscles as they tend to move around a lot during the throwing motion. Measurements on the thorax are performed using an IMU placed on the spine on the back of the user at the same height as the sternum (2). This configuration makes it significantly easier to connect the wiring as opposed to placing it on the sternum even though measurements might be affected by the movement of the scapulae (shoulder blades). The motion of the pelvis is done using an IMU between the pelvic bones of the spine (1).

IMU connection to the shirt

The performance of the IMUs is highly influenced by its attachment. The quality of the data decreases when the sensor can move relative to the shirt. Consequently, the attachment should be to such an extent that it is a part of the shirt and the person wearing it. Furthermore, protection of the sensor is crucial for its quality and durability. Since the construction with which the sensor is mounted on the shirt also protects it, both are looked upon at the same time.

The following criteria are used to evaluate the different concepts. First of all, the extent to which the sensor is protected is looked upon. Secondly, the weight and the size of the connection is important since the shirt should not hinder the pitcher. Replaceability is also an important aspect in case the IMU does not work anymore. Similarly the extent to which the attachment is waterproof is considered since water can damage the IMU. Finally, and most importantly, the quality of the connection is looked at. This encompasses the extent to which the sensor stays in place and does not interfere with the workings of the sensor.

In (appendix C) different attachment concepts can be found. An isolating pocket of fabric which is attached to the shirt using velcro and held in place even more rigidly with a strap has one big downside and that is that it is not waterproof. A 3D printed case scored highest overall. Different ways to attach the case to the shirt are possible. Using a snap button will keep it close to the shirt but still allows rotation along the normal axis. Using a magnet will disturb an added magnetometer on the IMU which is planned for further versions of the IMU. Velcro still allows some movement but the use of a connector sewn on the shirt that fits perfectly on the case will come close to an almost perfect connection to the shirt. A connection of that type will yield only reasonably little improvement compared to velcro and a strap. Moreover, designing a suitable connector would require time and careful consideration so a choice has been made to use the velcro. Ultimately a 3D printed case has been chosen which is attached using velcro and tightened to the shirt using a strap.

B. *Measurement of muscle activity*

The measurement of the muscle activity will be done using EMG. There are no major differences in the specifications of different EMG sensors, therefore the sensors provided by the university will be used, namely Physioplux (PLUX wireless biosignals S.A., Lisbon, Portugal).

EMG locations
The locations of the EMG sensors were determined using the guidelines in appendix D. To reduce noise a reference signal is used. For this reference signal a location without any muscle activity is desired. The easiest way to achieve this is by measuring the activity over a bone structure. The following locations for a reference signal have been considered: the cervical vertebra C7 (neck vertebra), the clavicle, the hip bone and the olecranon (elbow), each of which has its (dis)advantages in terms of ease of reaching the location, quality of the signal and how well the sensor stay in place.

A test has been performed to determine which location is the most suitable for the EMG reference (see appendix E). The clavicle proved to be the most suitable. It is close to the data acquisition device so it keeps the system light, compact and cable length is minimized.

EMG connection to the shirt
Several methods are available to measure the EMG signal. The first method is a disposable electrode which is for one time use only. It sticks to the skin and passes the signal to the sensor. Secondly gelled self adhesive stickers are an option. These can be used multiple times which is the only difference with the previous one. The third option is a dry conductive sheet in combination with a push button. The push button can be attached by conductive glue or using the first mentioned stickers. Lastly, contactless EMG is an option. hereby the sensor does not have to be in contact with the skin. This sensor type newly developed and needs a different data collection device compared to the EMG available from the TU Delft.

After considering multiple options regarding the EMG sensor on the shirt, a choice was made to use conductive fabric and a snap button. The lifespan of the reusable stickers is too short and the wireless EMG is too expensive. For a morphological overview see appendix F. Furthermore, the part of the EMG where the sensor is located is attached to the shirt using velcro to reduce movement of the sensor and therefore noise. More about these findings can be found in appendix G.

C. *Wiring*

The main function of the wires is the transfer of the signals between the sensors and data collecting devices. Furthermore, they should not hinder movement. A wireless connection would be the perfect option for this shirt, but the need for a power source and transmitter for each sensor would make them too heavy for the intended purpose. To maximise comfort and minimize interference with the pitching movement the data from the sensors will be sent to a central hub which will also contain a power source.

Material choice A suitable material to transfer the signals and power supply is insulated stranded copper wire, which can be considered standard wiring. They are cheap and easy to get, but not stretchable. This is a disadvantage when implemented in the shirt, because the full range of motion is restrained unless extra wirelength is added. The extra loose wiring can hinder or irritate. Two options are mentioned in the next paragraphs to solve this.

The first option is using an alternative conductive material. The alternative materials worth mentioning are conductive ink and conductive thread. A similar research by Yasunori et al. uses conductive ink to connect ECG sensors [28]. This method requires a printer which prints conductive ink, which is not available for this project. The same goes for sewing conductive thread into the shirt, this is difficult to manufacture and outside the scope of this project. So a different conductive material will not be used.

The second solution to solve the problem is an elastic material combining with the standard wiring to create a stretchable configuration. There are two options for the configuration with stretchable materials, namely a waveform (a) and a spiral form (b), these are shown in Fig. 1.

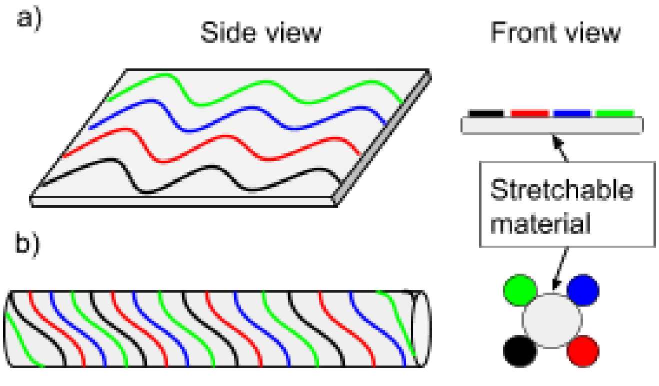

Fig. 1. Possible configurations for stretchable wiring

Because making the configuration by hand is difficult, two manufacturers per configuration have been selected. The data is shown in appendix H. The waveform wire from Ahmor seems the best option, mainly because of the cost. Moreover, the EMG wiring can not be changed and is not stretchable, so configuration (a) is chosen to make it stretchable.

1) Wiring location: For the wires it is prefered to take the way of the least amount of strain. This ensures that the strain on the shirt and the resistance to move will be minimal. To do this the wires are led over the rotational axis of the joints. The elbow has one axis of rotation so there are two possible attachment points. It has been seen that the connection point on the top of the arm is more suitable because there the wire stretches less when rotating the lower arm. The shoulder has three axis of rotation, having a center of rotation inside the shoulder. The acromion could be used for a connection point. Another option would be the most direct way. A test was held to figure out which route the least amount of strain compounds. This was done empirically by putting the user in the minimal and maximal moving positions. The route over the acromion proved to be the best.

2) Wiring connection to the shirt: A main requirement is that the shirt is washable (see appendix A, hard requirement 4). This can be achieved by making the wiring either washable or detachable. It is empirically found that the solder connection tends to fail when washed. Furthermore the wires become more irritable in comparison to the wires that are only attached to the shirt at the ends (see appendix I). Therefore the wires have been made detachable by attaching them using velcro.

The result of the detachable wire is that there are two options for the connection between the wires and the IMUs, a rigid and a modular connection. For the rigid connection, soldering is an option. For the modular connection a connector can be used. To meet the wishes (appendix A, wish 6) and make the shirt as modular as possible the connector was chosen. A friction based connector was used which is cheaper compared to a form fitted connector.

D. Data collection and processing

To collect the data from the sensors a central storage device is installed which can either send out the data directly or store it internally so it can be downloaded afterwards. In this device, from now on called the ‘hub’, the signals from the IMU and EMG are stored. It is 3D-printed and contains the arduino, EMG hub, an IMU and has room for a buzzer to provide feedback to the user.

Hub location
It is important for the hub to be easily reached by all the sensors and it should not hinder the athlete. Consequently the hub should be in a central position where little movement of the body takes place. The following locations are considered:

- The left side of the hip
- The central back side of the hip
- The left side of the shoulder
- The central back side between the shoulder blades

The location between the shoulder blades has been chosen since it is easy to reach and does not hinder the athlete.

Hub connection to the shirt
For the connection of the hub to the shirt the same possibilities as for the IMU and wires exist. Ultimately a choice has been made to attach it using velcro.

Software
Since a choice is made to use a certain EMG, the available software is immediately narrowed down. The EMG sensors are built in such a way that it is hard to use another interface or other software to interpret the results from the EMG. The data from the IMUs are interpreted using Matlab® (The MathWorks Inc., Natick, MA, USA).

Connection diagram
The IMUs are connected in two pairs of two IMUs which are connected in series. The signal from the first IMU in the series can be sent through the second one. In this configuration the second IMU is connected on both sides enabling to send through both its own data and the data from the first IMU. This makes the whole configuration more efficient and less wiring is needed. The way the sensors and the arduino are connected can be found in appendix J.

IV. RESULTS

In the results the chosen concepts from the four main components and the design results are put together to make the final prototype. This final product will be addressed shortly and tested in the following chapter.

A. Final product

The final prototype can be seen in Fig. 2 accompanied by a schematic view in Fig. 3. This visualization of the prototype shows the exact locations of the IMUs, EMG sensors and the hub and the path the wiring follows.

B. Prototype testing

In this chapter the final prototype is tested on the basis of the requirements. There is looked upon the quality of the sensors, the influence on performance the washability and the user friendliness.

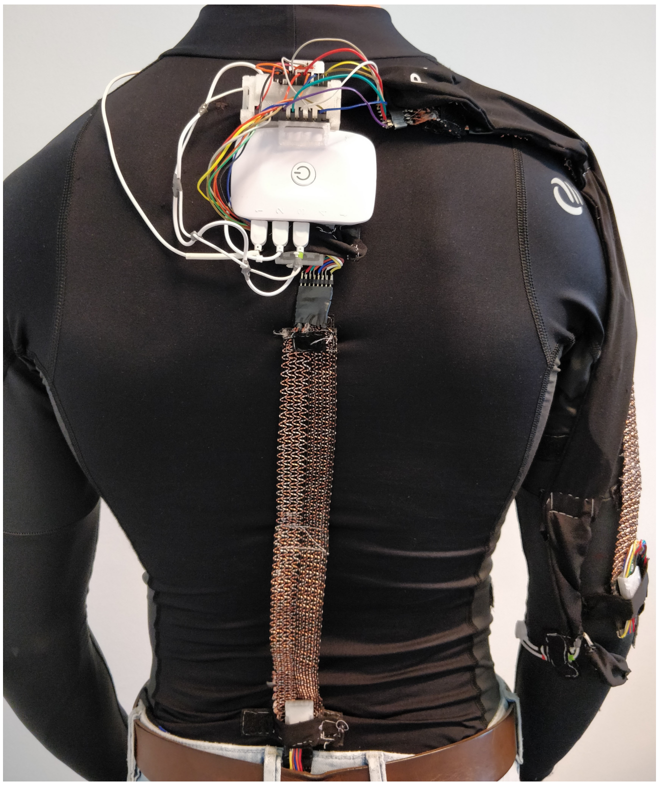

Fig. 2. Final prototype worn by test subject

Quality IMUs
The IMUs used in this project measure the acceleration in the x-, y- and z-direction and the angular velocity in the x- and y-direction. In this case, the elbow and wrist IMU were measured. The quality of the signals depends on multiple variables which are considered in the following chapter. The displacement of the IMU will not be measured, because it is assumed that it has less influence on the performance when it moves after a throw. The displacement during the throw however is relevant for the quality of the signal. Taking movement during the throw into account was not a priority in this project because the movement was assumed to be little and the data did not have to be perfect yet.

Noise measurements
First of all, the noise is an important factor in determining the quality. An experiment (see Appendix K) with the two IMUs has been performed. The signal of the IMUs was measured during 10 seconds when no movement was performed. These measurements were compared to the measurements done by the VU (Vrije universiteit, Amsterdam) in lab setup. The gyroscope noise signal of the Wrist IMUs from the shirt and from the VU are displayed in Fig. 4 and Fig. 5.

The analysed signals have an offset from zero, indicated as the accuracy error. The deviation around their mean is called the precision error. The accuracy and the precision errors were calculated in Appendix L to compare the quality of the IMU signal of the shirt with the IMU signal from the lab setup. The average errors were denoted in Table I

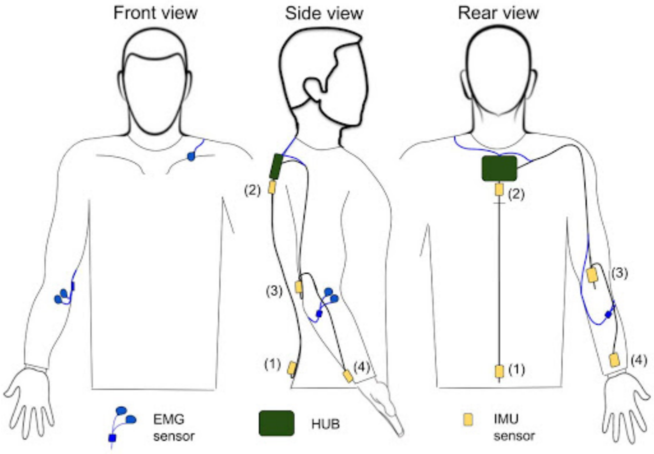

Fig. 3. Exact distances of the IMUs and lengths of the wiring

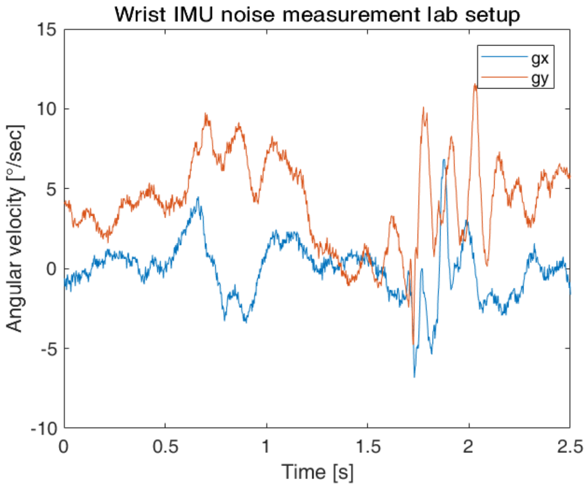

Fig. 4. Wrist IMU noise measurement of the gyroscope in lab setup

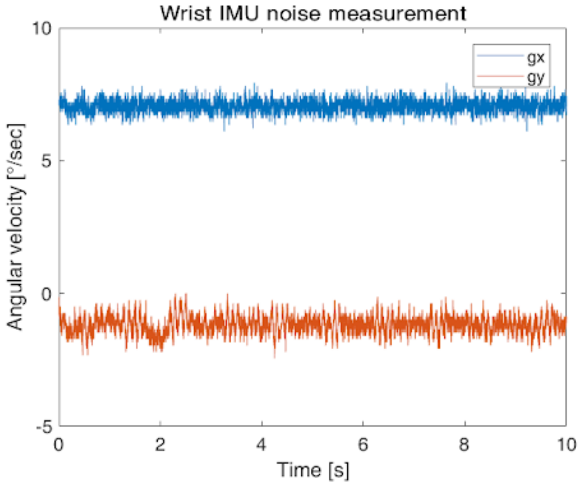

Fig. 5. Wrist IMU noise measurement of the gyroscope in lab setup

TABLE I

SIGNAL OFFSETS OF THE SHIRT IMUS AND THE LAB IMU

Offsets from 0	Wrist shirt	Wrist lab
Accelerometer accuracy error	0.48 g	0.36 g
Gyroscope accuracy error	4.12 °/s	2.06 °/s
Accelerometer precision error	$3.10 \cdot 10^{-3}$ g	$9.33 \cdot 10^{-3}$ g
Gyroscope precision error	0.235 °/s	1.725 °/s

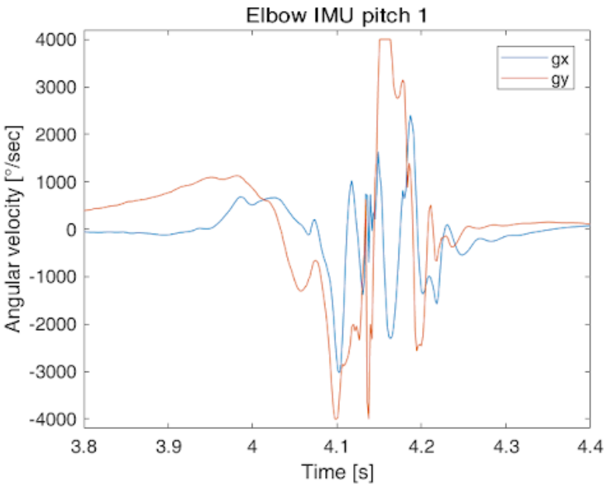

Fig. 6. Elbow gyroscope signals during pitching

Out of the table appears that the measurements with the shirt are less accurate but more precise than the measurements retrieved in the lab setup. Because the accuracy can be calibrated, a comparable accuracy with the lab setup is not required for the shirt IMUs. In this case the precision is correlated with the noise. For the shirt IMUs, there was found that the signal contained 66.7% less noise for the accelerometer signal and 86.4% less noise for the Gyroscope signal. Out of these findings, the requirement is reached that the IMUs contain not more than 10% noise than the lab setup IMUs.

Signal quality during pitching

Multiple pitches were performed and the IMU signals were measured (Appendix I). The angular velocity of the elbow and the acceleration of the wrist are displayed below in Fig. 6 and Fig. 7.

These measurements were compared to an earlier study done by Lapinski et al. [26]. In the study mentioned above accelerations and angular velocities were reached up to 80 g's and 5,000 °/s. During the experiment in this study the maximum range of the sensors was exceeded (accelerometer: 30 g, gyroscope: 4000 °/s) and clipping occurred. This means that no conclusion regarding the peak values can be drawn. What can be said is that the time domain of the pitch (duration of the pitch is ca. 0.5 s) is roughly the same and that an acceleration and a deceleration were measured at respectively the beginning and the end of the pitch. Some similarities thus can been observed but no significant conclusions can be drawn.

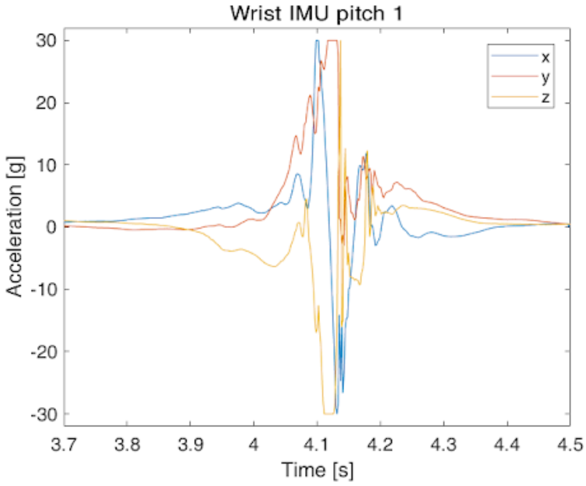

Fig. 7. Wrist accelerometer signals during pitching

Quality EMG sensors

The quality of the measurements done by the EMG sensor are determined by the quality of the sensor electrodes. The electrodes are fixated on the shirt and are guided to the skin via conductive sheet. Therefore, the measurements done by the shirt are compared with the signal response of a gelled electrode on a shaved skin which is cleaned with alcohol (commercial product: Gelled Self-adhesive Reusable Ag/AgCl from Plux). This signal response will be referred to as 'the gold standard'. The EMG signals measured with the electrodes in the shirt at the pronator teres and the extensor mass are compared with the gold standard. In the experiment a flexing, an extending and a pitching movement have been performed with the right arm. Each movement was performed five times. The results can be found in Appendix N.

Sensor displacement

By performing a baseball pitch the shirt will move slightly over the skin. An experiment has been conducted to observe the displacement of the shirt (see appendix O). The outcome of the experiment shows that a dry electrode on the pronator has a maximum displacement of 5.3 mm after three pitches. A wet electrode is displaced with a maximum of 2.1 mm after three pitches. This concludes that the shirt meets the requirement of a maximum displacement of 1 cm radius.

Noise measurement

To determine the noise when no muscles are contracted, an experiment has been conducted in which the noise was measured during one second. This data was extracted from the experiment described in Appendix J. During this experiment, the test subject wore the gelled electrodes, the shirt with dry EMG electrodes and the shirt with wet EMG electrodes. The results of the EMG-signal are shown in Table II.

From the results can be concluded that the dry electrodes

TABLE II

NOISE MEASUREMENTS OF DIFFERENT SIGNALS WITH NO CONTRACTION OF THE MUSCLES

Noise measurement (mV)	Golden standard	Dry electrodes	Wet electrodes
Pronator teres	0.0016	0.0065	0.0017
Extensor mass	0.0029	0.0478	0.0016

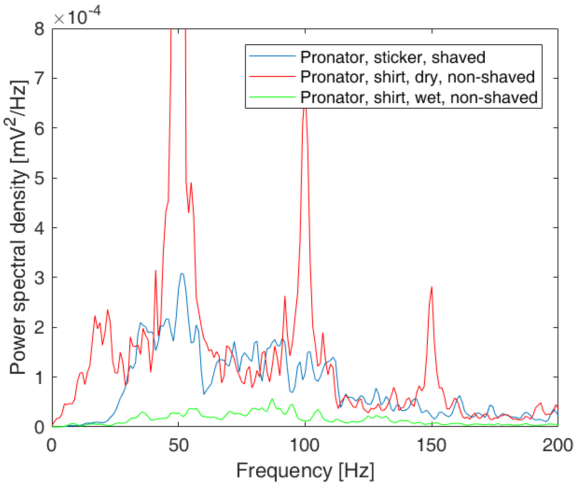

Fig. 8. Power spectral densities of the signals at the pronator teres

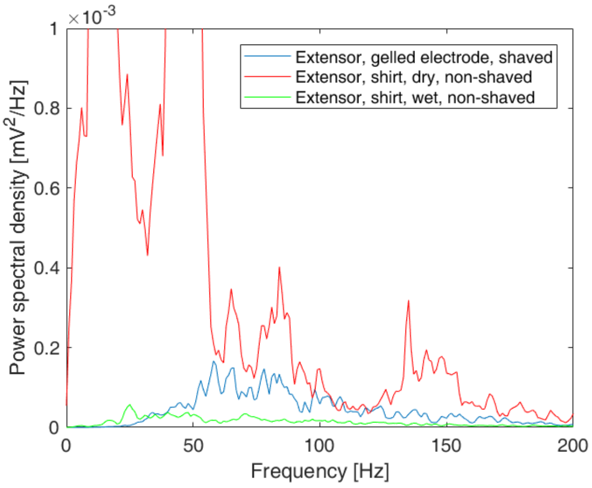

Fig. 9. Power spectral densities of the signals at the extensor mass

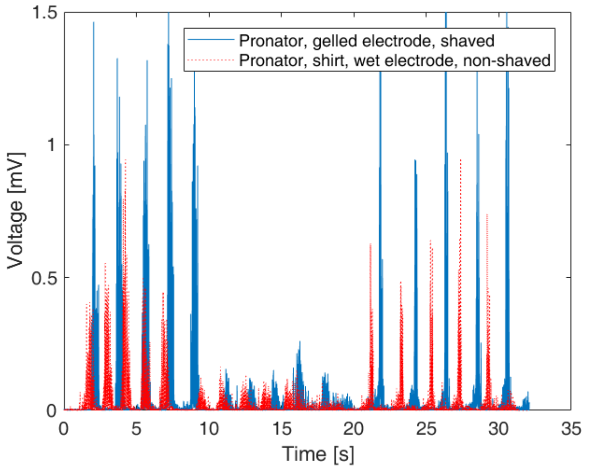

Fig. 10. The golden standard signal and the wet electrodes signal at the pronator teres

contain significantly more noise than the golden standard making the signal less useful. Furthermore, the wet electrodes showed less or a comparable amount of noise compared to the golden standard. The requirements state that the noise of the electrodes should not be more than 10% above the golden standard. The noise that is measured with the wet electrodes at the pronator deviates 6.25% from the gold standard and contains 45% less noise at the extensor mass.

Power spectral densities

The power spectral densities in Fig. 8 and Fig. 9 denote the power per frequency, which are related to the noise during contraction of a muscle.

In this case, the different signals from the pronator teres and the extensor mass are compared. Table II showed that dry electrodes contain more noise than a gelled electrode when no movement is performed. From the graph can be seen that the power spectral density of the dry electrodes has a significantly bigger magnitude. This implies that the signal from the dry electrode has more noise than the gold standard, also when the specific muscle has been contracted.

The power spectral density of the wet electrodes has a smaller magnitude than the gold standard. This could mean multiple things. Firstly it could mean that the signal could be less noisy. The noise measurement in Table II also shows that the wet electrodes have a comparable or less amount of noise at the pronator and the extensor. The same result was found in the study done by C. Pylatiuk et al. [29]. The other possibility would be that the signal has less strength when the muscle is contracted. To test this option, the signals that are obtained out of the experiment results in Appendix O are compared to each other in the same graph.

Because the EMG measurements were performed at slightly different timings, the signals are out of phase. The graphs in figure x indicate that the signal from the wet electrodes show the similar pattern compared to the gold standard signal. The averages were determined for the peaks of the contractions of the specific muscles. The peaks of the gold standard were on average 1.41 mV at the pronator teres and 1.2 mV at the extensor mass. With the wet electrodes on the shirt, peaks of on average 0.55 mV at the pronator and 0.38 mV at the extensor mass were obtained. Although in this experiment the peaks from the wet electrodes on the shirt are smaller, a similar pattern between the gelled electrodes and the wet electrodes on the shirt can be seen. There has to be taken into account that the signal during contraction decreases with on average 65% for the pronator and 68% for

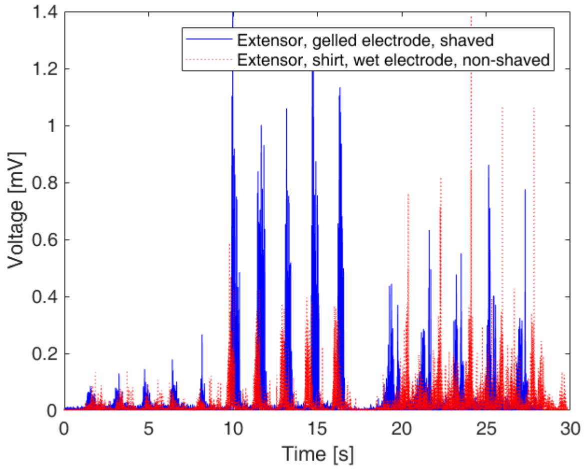

Fig. 11. The golden standard signal and the wet electrodes signal at the extensor mass

the extensor. As stated in the requirements, the peaks may not deviate more than 20% from the gold standard. This is clearly not reached, but there is still a significant relation between the muscle contractions and the peak signals. The decrease in the peaks is assumingly caused by containing less noise. Therefore the signal is considered usable.

Influence on performance
The performance of a pitcher is measured by the speed of the ball when thrown with equipment and without equipment on the shirt. In this test the requirement of the shirt having a minimal effect on the ball speed is tested. Fig. 12 shows that the average ball speed of the test with equipment on the shirt lies in the range of the average ball speed without equipment. The maximal difference was 1.39 km/h (2.3% of the average). Furthermore, a paired sample t-test was performed to compare the means from the same user at two different instances. This test yielded a t-value of 0.021 meaning both sets of data show a lot of similarity. The influence of the shirt meets the requirements of having a maximum effect on the ball speed of 5%

Washability
To test the shirt, it was washed for an hour in 40°C. The result was that the velcro stayed on the shirt and had no change in adhesive strength. Secondly, the EMG-electrodes with the conductive sheet that is sewn in the shirt, still give a similar signal response compared with the non washed EMG-electrodes. therefore the shirt meets the requirement of being washable.

Taking the shirt on and off
The shirt has been tested on user friendliness and durability concerning taking the shirt on and off. The results of the tests show that the shirt does not meet requirement 5 and wish 9 (appendix P). Components got loose and it rated on comfort significantly less than the shirt without equipment on.

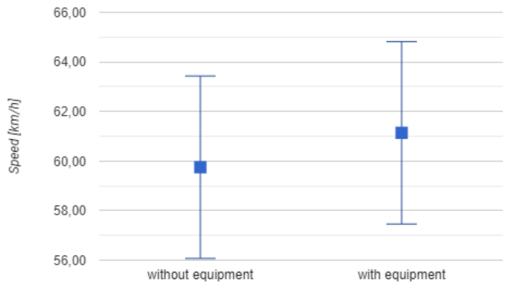

Fig. 12. Mean and one standard deviation of ball speeds thrown with and without equipment

V. DISCUSSION

Reflecting on the results lead to two parts. Firstly, the tests and corresponding data are reviewed. Afterwards, points of improvement on the final prototype are discussed.

To start off with, the second string of IMUs located on the back of the user has not been tested. No conclusions regarding its working can thus be drawn. The first string of IMUs on the arm has been tested. Since the IMUs were not able to measure the high acceleration and angular velocity, clipping occurred which made the data less useful. The precise location of the peaks could have been interpolated. This would enable the possibility to say something about the kinematic chain since at the time of the peak the next body segment should start rotating. Furthermore, the noise measurements done with the shirt are much more stable than the measurement done in the lab where still some peaks are visible. Because those measurements were performed by another party, the possibility exists that the IMUs were slightly moved during the measurement. This could have caused the peaks in the noise measurement.

The EMG measurements met two of the three requirements. Although the peaks of the shirt measurements did not lie in the 20% range of the gold standard, the signal showed a similar pattern compared to the gold standard. It is possible that the smaller peaks were caused by less noise of the wet electrodes. This statement is supported by the noise measurement and power spectral density. If this is true the signal performed better than the gold standard. The data from the EMG sensors could have been more reliable. The test as it was done now was by simply flexing and tensing the muscle without any guideline regarding the amount of tension that should have been applied. This resulted in different amounts of tension between tests. It could have been more reliable by making the tests ‘max effort’ tests probably resulting in more consistency.

The EMG sensors and the IMUs were not tested at the same time. When the sensors would be measuring at the same time, there could appear interference between the sensors that could influence the signal.

When looking at the data from the ball speed test an unexpected result was obtained. On average the ball was thrown at a higher velocity when everything was in place compared to when only the shirt was on. A t-test showed that both sets of data correlate strongly so the difference is not significant. Since an inexperienced pitcher was used, the possibility exists that the shirt would hinder a professional pitcher since much higher speeds would be reached.

The sensor displacement test of the EMG yielded some interesting results. After three pitches it was evident that the sensor was moving in a linear fashion. The test however was stopped after these three pitches so the further course of the sensor after performing more pitches is not clear yet. More pitches should be done to fully know how the EMG sensor would move.

Looking at the size of the hub results in difficulties when taking off the shirt. The hub thus has to be attached and detached when putting the shirt on and off, which can not be done by the user. The need for an extra hand reduces the user friendliness of the shirt.

When looking at the final prototype the central hub is fairly large and placed in a location where there is no direct contact to the body. Consequently the hub ‘floats’ between the shoulder blades. The combination between the size and location results in a moving hub during the pitch which can hinder the user.

The obtained signal from the first string of IMUs has not been synchronized with the EMG signal. Because of this the relationship between the muscle activity and kinematic chain could not have been explored.

VI. CONCLUSIONS

The goal of this design study is to develop a shirt that can track the kinematic chain and the muscle activity of relevant muscles during a throw of a pitcher. A shirt of that nature enables users to perform measurements outside of the lab which can help give insight in injury prevention of overhead sports.

The shirt takes shape in the following way. The data is transferred via stretchable cables to a central hub. This is the best way found to keep the components on the arm as light as possible leaving little interference with the pitching throw. The hub itself contains possibilities to store or send out measurements. The protection and connection of the sensors are accounted for via 3d printed casings and extra straps over the components. The sensors performed as expected compared to the gold standards this project has set.

To conclude, a successful prototype has been developed. With the different sensors the prototype can map the movement and track the muscle activity of relevant muscles, which can be insightful for injury prevention and takes the measurements onto the field. This was the goal of the project, concluding that the prototype achieved what was intended.

VII. RECOMMENDATIONS

Performing measurements is currently done in a continuous fashion meaning the system is never ‘off’ and consumes a lot of energy. Moreover will it result in a large string of data which is hard to interpret. The software used to process the data from the IMUs already contains a trigger which detects when a pitching movement starts and when it ends. This trigger powers the system on and off and starts and ends the measurement. This enables the system to stay in stand by and thus conserve energy. This trigger can also be used to send a block signal over the EMG during the pitch. This would define the parts in the data where the actual pitch was performed for both the IMUs and the EMG. In this way it would be easier to compare the data from the EMG and IMU when a pitcher throws the ball.

The prototype which was designed was custom made and thus a perfect fit for one specific user. If the shirt would be used by somebody with a different height or body type the sensors would not be in the correct place. Making different shirt sizes with sensor in the appropriate locations would be advised to obtain optimal results for different body statues. More about this can be found in appendix Q. Since the amount of throws directly correlates to the risk of injury, feedback regarding the amount of throws would be advised. In order to provide this, a buzzer located on the central hub would be a logical option. The arduino would track the amount of pitches performed and notify the user every certain amount of throws of the amount of balls thrown that training.

For this prototype, in order to make the shirt more user friendly the wires and sensors could be covered using an extra piece of fabric making it easier to put on the shirt.

For further studies the first objective would be to make the sensors wireless. Wireless sensors would avoid numerous problems. The available wireless sensors right now are simply too big and too heavy to be suitable for the shirt. Moreover the quality of the IMUs could be improved. The sensors used for this prototype simply could not measure the high acceleration and angular velocity. A second option would be to look into printing conductive ink or sewing conductive thread. This would remove weight and parts resulting in a more user friendly shirt. Another recommendation when continuing with this prototype is to validate if the data from the EMG and the IMUs are comparable to the data acquired from measurements in the lab.

Finally a big issue that could be addressed would be the UCL. An injury to that ligament is the most common injury in baseball and a direct way to monitor its status would be ideal [5]. Temperature sensors for example could be looked into to know more about its temperature and in turn help to guide warm-ups.

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APPENDIX A

Requirements, conditions, and wishes

Hard requirements

1) The sensors have to be able to measure the angular velocity during the throwing movement of the lower arm, shoulder, chest, and hip.
    a) The noise of the signal must be comparable with the noise of the gold standard measurement, within 10%.
    b) The average peak values of the signal during contraction must be similar to the golden standard, within 20%
2) The shirt has to be able to measure the electric muscle activity of the pronator teres and the extensor mass. Therefore:
    a) The EMG sensors in the shirt have to stay in the correct position over time. moving within a maximum radius of 1 cm.
    b) The noise of the signal must be comparable with or lower than the noise of the gold standard measurement, within 10%.
    c) The average peak values of the signal during contraction must be similar to the gold standard, within 20%.
3) The shirt should affect the speed of the ball as little as possible, 5% maximum.
4) The shirt has to be washable.
5) The shirt has to be able to be put on and taken off for at least 5 times in a row without damaging it or the attached components.

Conditions

1) The shirt can not be irritable after a time span of 1 hour.
2) The shirt can not affect the health of the user in a negative way.

Wishes

1) The shirt has to be as light as possible.
2) The fitting of the shirt has to be generalised for as many users as possible.
3) The shirt needs to affect the environment as little as possible.
4) The shirt needs to be as cheap as possible.
5) The shirt has to be able to be put on and used in as few steps as possible.
6) The shirt has to be easily adjustable.
7) The measurements of the IMU and EMG sensors have to be able to be synchronised.
8) The shirt has to be able to start a measurement when a pitch takes place.
9) The shirt has to be as user friendly as possible with taking the shirt on and of and in use.

APPENDIX B

Overview of different IMUs

TABLE I
IMU TYPES

Sensor	**Input range (°/s)**	**Sample rate (Hz)**	**Volume (mm^3)**	**Price**
ADIS16470	2000	2000	11x15x11	$149
BMI270	2000	1600	2.5x3.0x0.8	Unknown
MPU-9250	2000	4000	3x3x1	$14.95
MPU6050	2000	1000	4x4x0.9	$9.90
TU IMU	4000	1000	2.3x1.6x1	$0

APPENDIX C

Comparison of the different connection possibilities

TABLE I

MORPHOLOGICAL OVERVIEW OF CONNECTION POSSIBILITIES TO THE SHIRT

	Pocket	**Snap button**	**Velcro**	**Plastic connector**	**Magnet**
Connection strength	++	++	+	++	+
Chance of movement	-	-	++	++	++
Comfort	++	+	++	+	+
Attachable to the shirt	+	+	++	+	+

APPENDIX D

EMG-sensor locations

To measure the correct muscles, the location of the selected muscles must be known. The pronator teres can be found between the 2 and 3.5 cm from the middle line of the medial epicondyle and the bicep tendon [9]. In contrast to the pronator, the extensor muscle mass is located empirically. With the use of the Physioplux system and two reusable stickers, the location with the best signal response has been chosen for the EMG electrodes locations. For the first electrode, the location was found on the same line as the medial epicondyle and at the highest point of the cross section when the arm is stretched. The second electrode is placed 3 cm further along the extensor mass in direction of the wrist, this can be seen in Fig. 1.

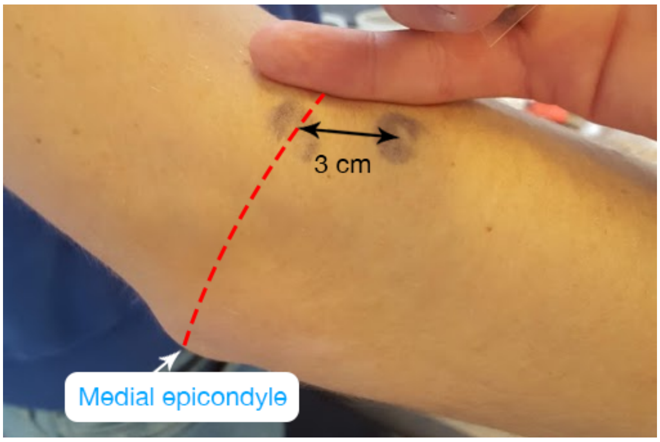

Fig. 1. EMG electrode locations at the extensor mass

APPENDIX E

EMG reference location comparison

TABLE I

MORPHOLOGICAL OVERVIEW OF EMG REGERENCE LOCATIONS

	Convenience location determination	**Convenience holding the sensor in place**	**Quality signal**
Forehead	++	++	++
Clavicle	++	+	++
Hip bone	+	+	-
Elbow	+	–	-
Cervical vertebra	+	-	–

APPENDIX F

EMG connection to the shirt comparison

TABLE I

MORPHOLOGICAL OVERVIEW OF EMG SENSOR CONNECTION TO THE SHIRT

Method	**User friendliness**	**Quality signal**	**Reusability**	**Cost**
Sensor sticker	-	++	–	+
Conductive material	++	+	++	++
Contactless EMG sensor	++	++	++	–
Gelled self adhesive reusable	+/-	+	+	+

APPENDIX G

Reducing noise in the EMG-sensor

The conductive sheet is sensitive to noise and disturbances because of its labile contact with the skin. Therefore an experiment has been performed to obtain a better insight in the quality of the signal response with the conductive sheet electrode. The prototype of the shirt was pulled on a test subject and the test subject was asked to fully relax the lower arm muscles. The shirt measured the pronator teres on the right arm and reusable electrodes were placed on the pronator teres of the left arm, this is displayed in Fig. 1. Both the arms were moved by an external person during the time that the test subject was relaxing his muscles. The signal that was obtained, is shown in Fig. 2.

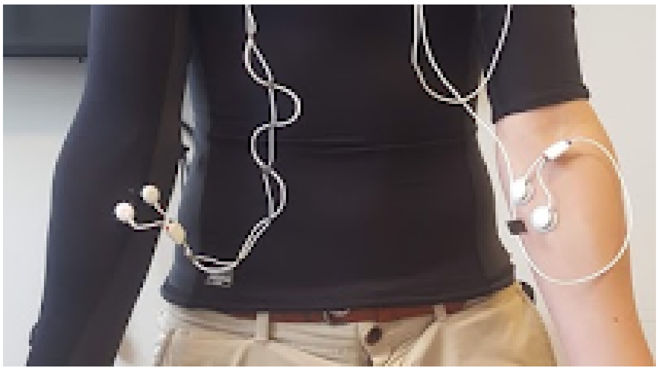

Fig. 1. Test subject with EMG-sensors connected

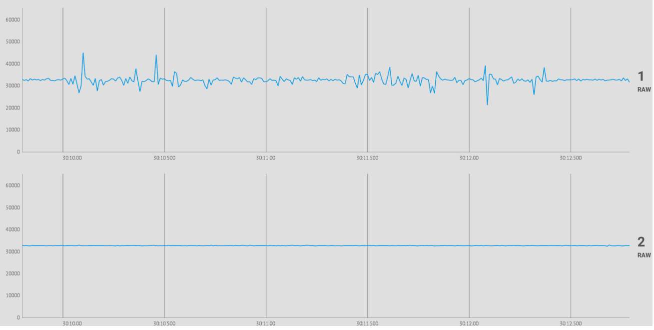

Fig. 2. Signal 1: Right arm (measured by shirt), Signal 2: Left arm (measured by reusable electrode)

The experiment showed that the shirt gives a noisy signal when the EMG-sensor is not tightened to the shirt. The experimental solution was found in Fig. 3. The signal response that was obtained after this adjustment is shown in the Fig. 4.

Fig. 3. EMG sensor taped to the shirt

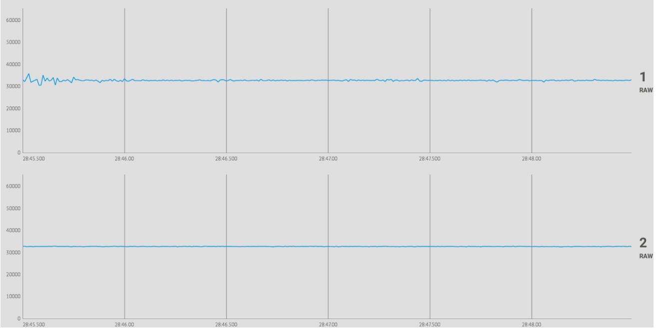

Fig. 4. Signal 1: Right arm (measured by shirt), Signal 2: Left arm (measured by reusable electrode).

APPENDIX H

Overview of stretchable wires

TABLE I

OVERVIEW OF STRETCHABLE WIRES

Type of wire	**Available**	**Price**	**Resistance**	**Connection**
Amohr (waveform)	yes	free sample	0.8Ω/m	soldering
Ohmatex (waveform)	yes	99 euro per 10m	0.4Ω/m	soldering
Roboden (spiral form)	yes	1000 euro per 10m	3.75Ω/m	soldering
iStretch (spiral form)	no response	-	-	-

APPENDIX I

Comfort of sewn wiring

During pitching training, the shirt has to be worn for an hour on average. Therefore, wearing the shirt has to be comfortable. An experiment has been conducted with 3 test subjects who wore the shirt for at least one hour. The test subjects were asked to grade the comfort of the shirt on a scale from 1 till 5, where 1 indicates “not comfortable” and 5 indicates “very comfortable”. Two tests were conducted with the stretchable wiring. The setups of both tests can be seen in Fig. 1. At first, the wiring was sewn in on the elbow, the results of this can be seen in Table I. In the second test the wiring was sewn in on the shoulder blade, the results of this can be seen in Table II.

Fig. 1. The test setups

TABLE I

FINDINGS OF THE TEST SUBJECTS AT THE ELBOW

Comfort stretchable wiring on elbow	**Rating with sewn in wiring (1-5)**	**Rating without wiring (1-5)**
Test subject 1	2	5
Test subject 2	2	5
Test subject 3	1	4

TABLE II

FINDINGS OF THE TEST SUBJECTS AT THE ELBOW

Comfort stretchable wiring on shoulder	**Rating with sewn in wiring (1-5)**	**Rating without wiring (1-5)**
Test subject 1	5	5
Test subject 2	4	5
Test subject 3	4	5

Appendix J

Connection diagram

Concerning the hardware, the pcb containing IC20649 and AK00918c (IMU) should be connected to the HUZZAH32 arduino. As described earlier the IMUs are connected in two pairs of two in series. Consequently sensor 1 should be connected to sensor 2 and sensor 3 should be connected to sensor 4. This yields in the fact that only sensor 1 and sensor 3 are connected to the arduino. The IMUs are connected to each other as shown in Table I. The connection to the arduino is shown in Table II. An image of the IMU with numbered pins is shown in Fig. 1.

TABLE I
The pin connections for the IMUs

IMU 1 and 3	**IMU 2 and 4**
pin 13	pin 1
pin 14	pin 2
pin 15	pin 3
pin 16	pin 4
pin 17	pin 5
pin 18	pin 6
pin 19	pin 7
pin 20	pin 8

TABLE II
The pin connections for the IMUs to the arduino

HUZZAH 32 arduino	**IMU 1**	**IMU 4**
bat	pin 1	pin 1
pin 27	pin 2	pin 2
GND	pin 3	pin 3
pin 15	pin 4	pin 4
pin 14	pin 5	-
pin 21	pin 6	pin 6
pin A0	pin 7	-
pin A1(optional)	pin 8	pin 8
pin 32	-	pin 5
pin 33	-	pin 7

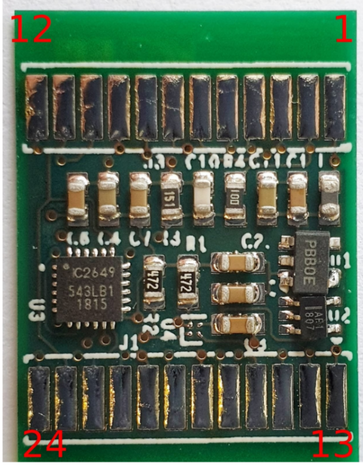

Fig. 1. The IMU with pin numbers(source: Vrije Universiteit Amsterdam)

The EMG connection diagram is shown in Table III. An image of the hub is shown in Fig. 2.

TABLE III
EMG wiring connection

	Sensor 1	**Sensor 2**	**Reference sensor**	**Signal from arduino**
EMG hub	1	2	⇓	⇔

Fig. 2. The EMG hub (source: PLUX wireless biosignals S.A., Lisbon, Portugal)

Appendix K

Noise measurements lab setup

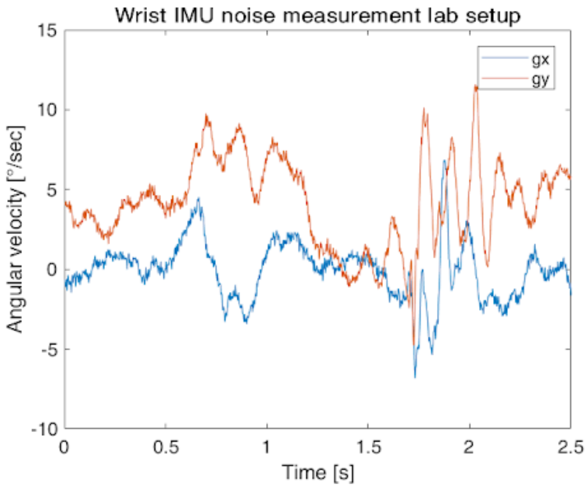

Fig. 1. Noise wrist gyro lab setting

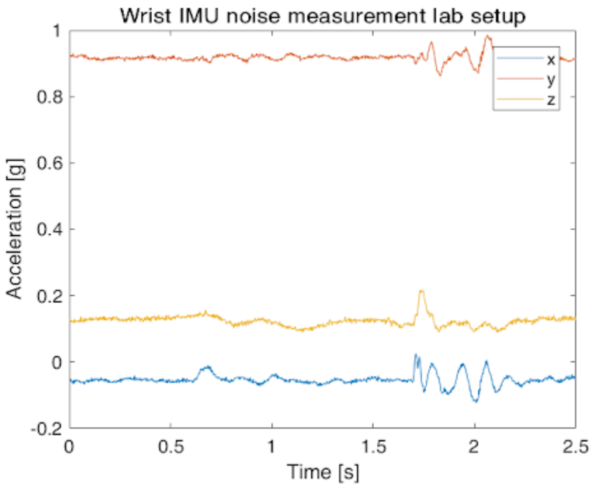

Fig. 2. Noise wrist accelerometer lab setting

Noise measurement shirt

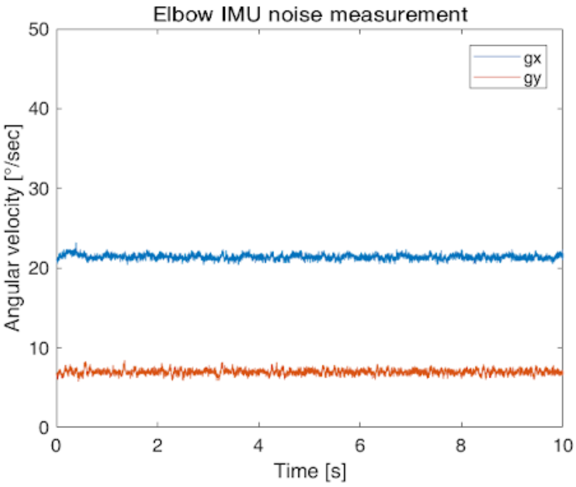

Fig. 3. Noise elbow gyro in the shirt

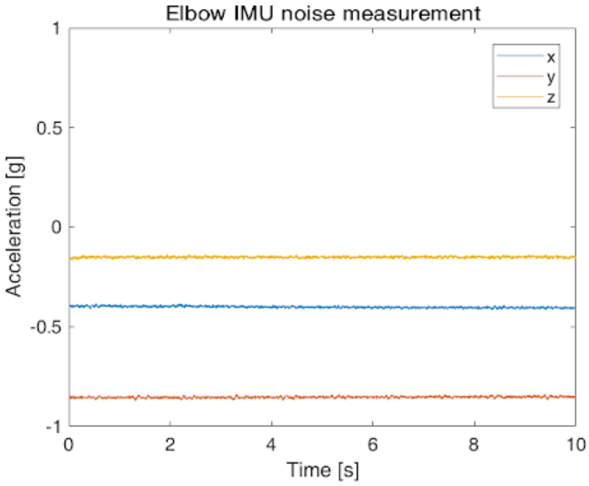

Fig. 4. Noise elbow accelerometer in the shirt

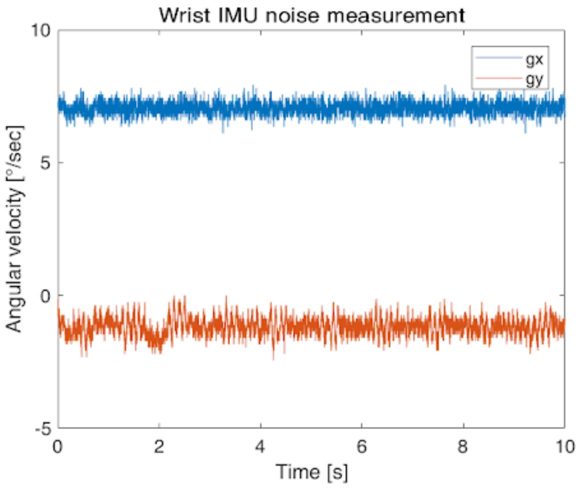

Fig. 5. Noise wrist gyro in the shirt

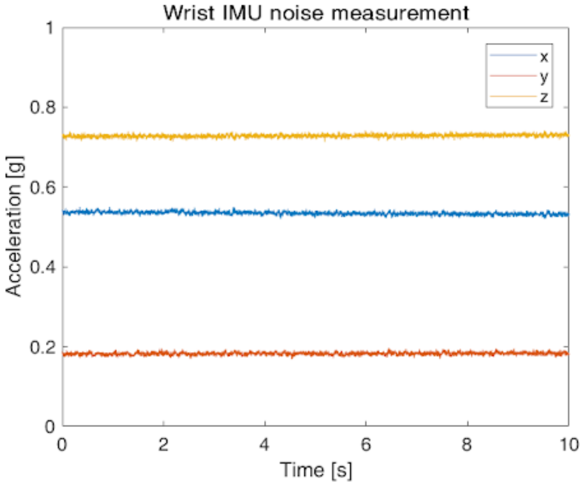

Fig. 6. Noise wrist accelerometer in the shirt

APPENDIX L

Accuracy and precision error determination

As can be seen from the figure the signal has an average offset from 0, also called the accuracy error. The same was found in all the other measurements which can be found in Appendix I. The accuracy errors from every measurement is denoted in Table I.

TABLE I

SIGNAL OFFSETS OF THE SHIRT IMUS AND THE LAB IMU

Offsets from 0	Elbow	Wrist	Wrist lab
Acceleration x	0.40 g	0.54 g	0.05 g
Acceleration y	0.85 g	0.18 g	0.92 g
Acceleration z	0.15 g	0.73 g	0.12 g
Gyroscope x	21.4 °/s	7.06 °/s	0.09 °/s
Gyroscope y	6.96 °/s	1.18 °/s	4.02 °/s

When measurements are done with the shirt the offsets must be taken into account and the shirt has to be calibrated.

Furthermore, the precision of the signal has to be calculated. Therefore the signal was calibrated and the precision errors were determined by the following formulas where x represents te signal.

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

$$x_{normalized} = |x| - |\overline{x}| \tag{2}$$

$$\overline{x_{normalized}} = \frac{1}{n}\sum_{i=1}^{n} x_{normalized,i} \tag{3}$$

The accelerometer and gyroscope signal noises were calculated and are displayed in Table II.

TABLE II

NOISE OF THE NORMALIZED SIGNALS

Noise	Elbow	Wrist
Acceleration x	$4 \cdot 10^{-3}$ g	$3.3 \cdot 10^{-3}$ g
Acceleration y	$3.5 \cdot 10^{-3}$ g	$2.9 \cdot 10^{-3}$ g
Acceleration z	$3.5 \cdot 10^{-3}$ g	$3.1 \cdot 10^{-3}$ g
Gyroscope x	0.25 °/s	0.20 °/s
Gyroscope y	0.26 °/s	0.27 °/s

APPENDIX M

Pitching data from the IMU sensors

Pitch measurement 1

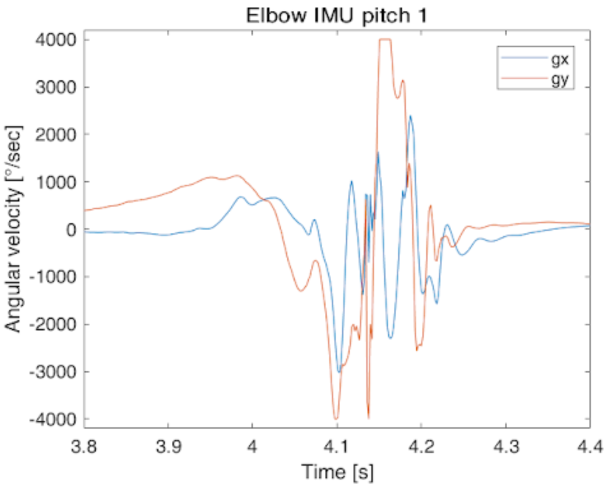

Fig. 1. Pitch 1, elbow IMU, gyroscope graph

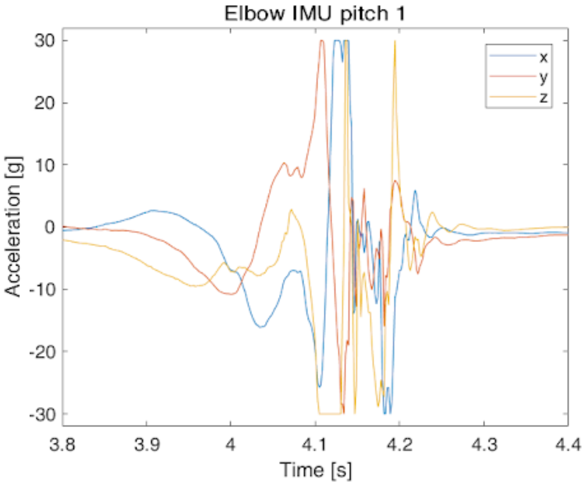

Fig. 2. Pitch 1, elbow IMU, accelerometer graph

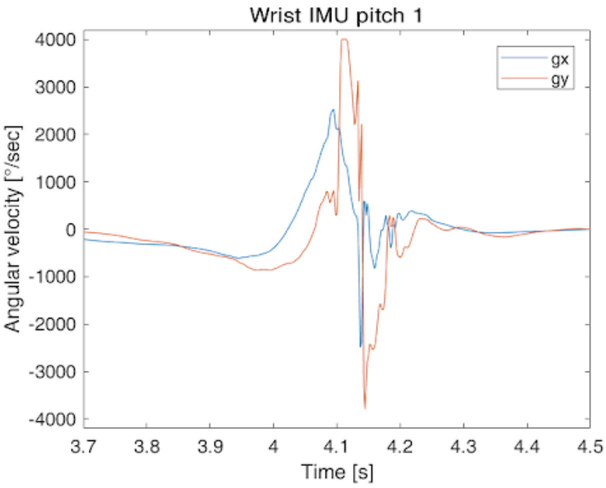

Fig. 3. Pitch 1, wrist IMU, gyroscope graph

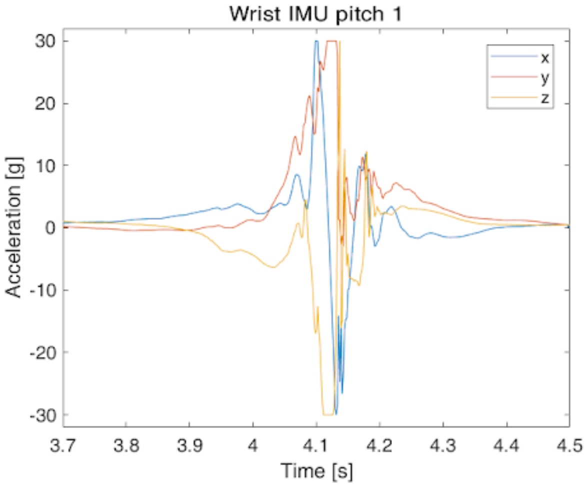

Fig. 4. Pitch 1, wrist IMU, accelerometer graph

Pitch measurement 2 (Thrown at 50% of maximum strength)

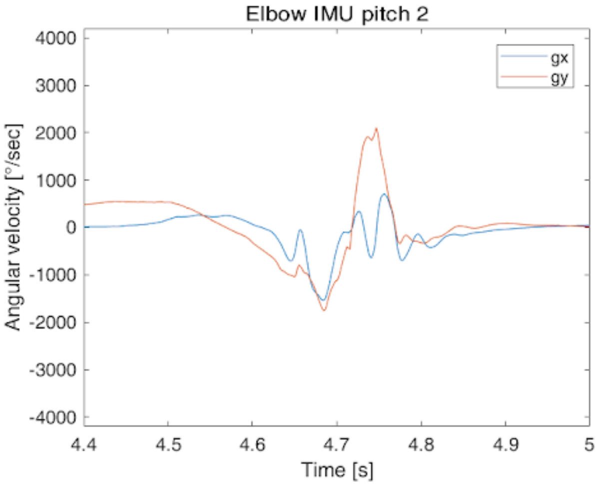

Fig. 5. Pitch 2, elbow IMU, gyroscope graph

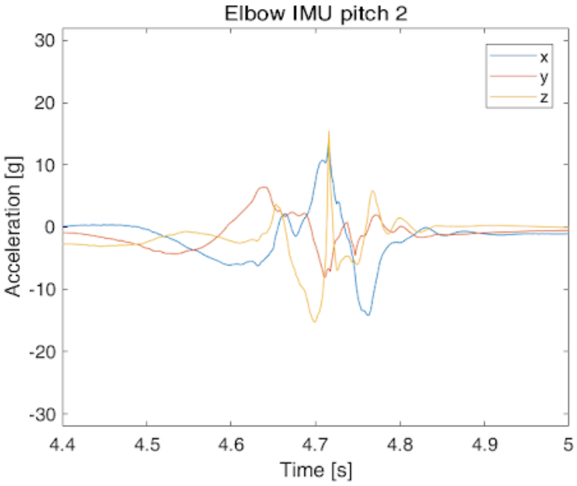

Fig. 6. Pitch 2, elbow IMU, accelerometer graph

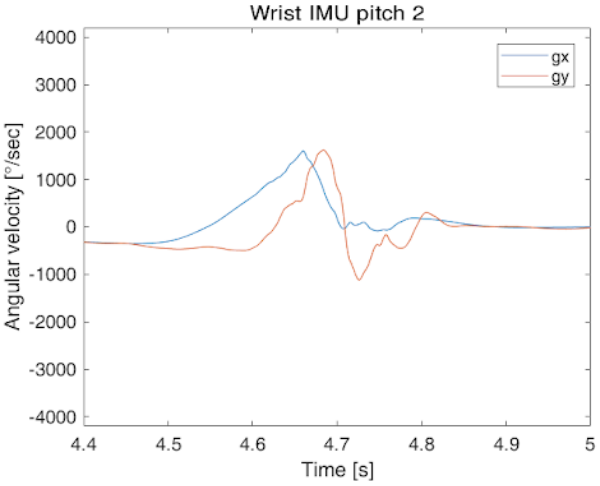

Fig. 7. Pitch 2, wrist IMU, gyroscope graph

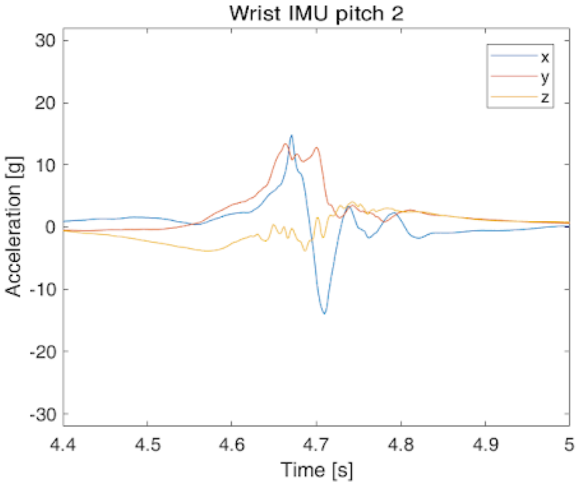

Fig. 8. Pitch 2, wrist IMU, accelerometer graph

Pitch measurement 3

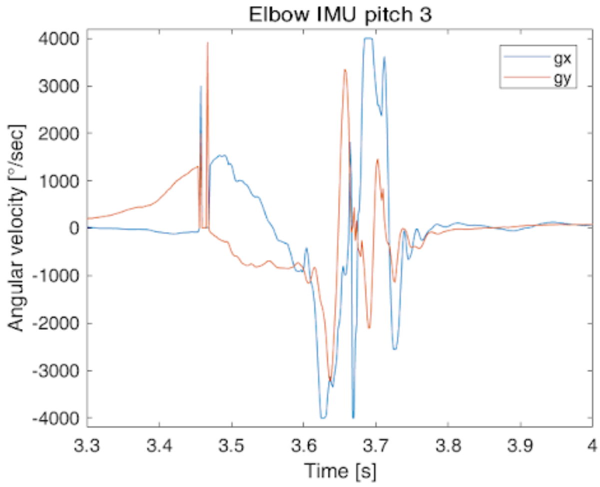

Fig. 1. Pitch 3, elbow IMU, gyroscope graph

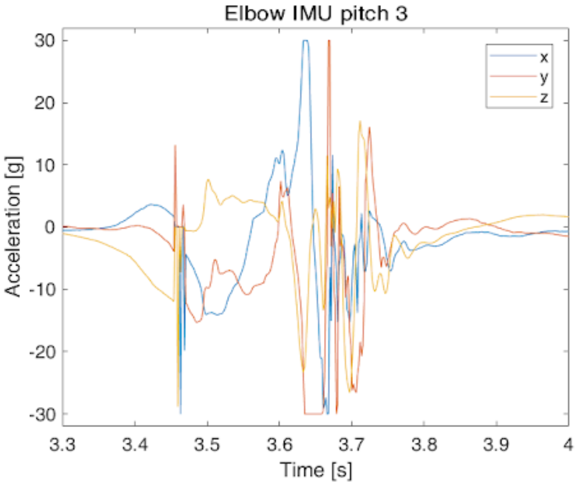

Fig. 2. Pitch 3, elbow IMU, accelerometer graph

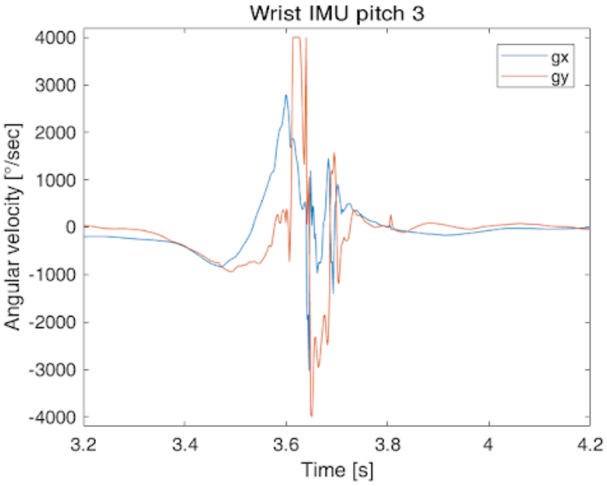

Fig. 3. Pitch 3, wrist IMU, gyroscope graph

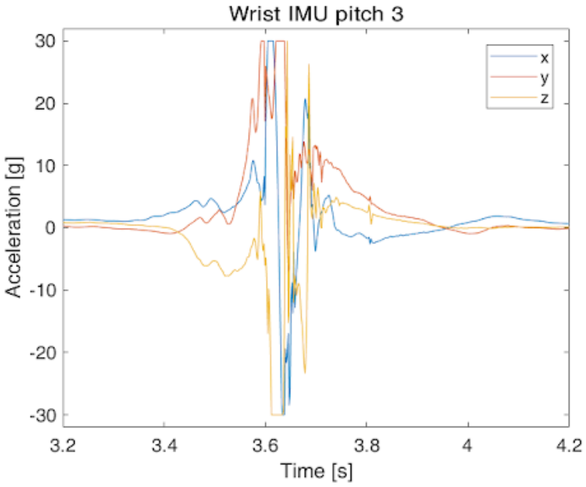

Fig. 4. Pitch 3, wrist IMU, accelerometer graph

Appendix N

Signal response EMG sensor with different electrodes

Signal response of gelled electrode on prepared skin at the pronator and the extensor

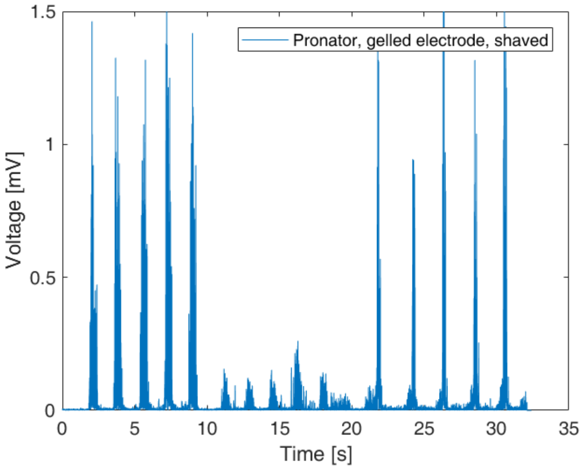

Fig. 1. Signal response of gelled electrode on prepared skin at the pronator teres

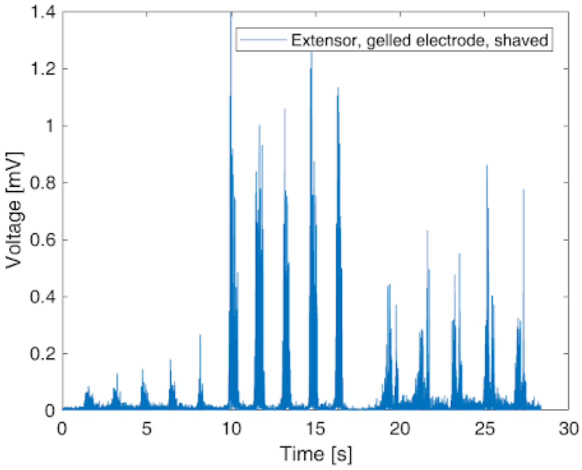

Fig. 2. Signal response of gelled electrode on prepared skin at the extensor mass

Signal response of the shirt with dry electrodes on unprepared skin at the pronator teres

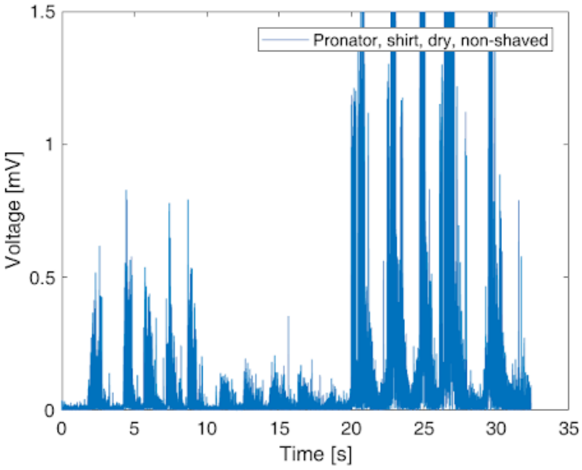

Fig. 3. Signal response of dry electrode on unprepared skin at the pronator teres

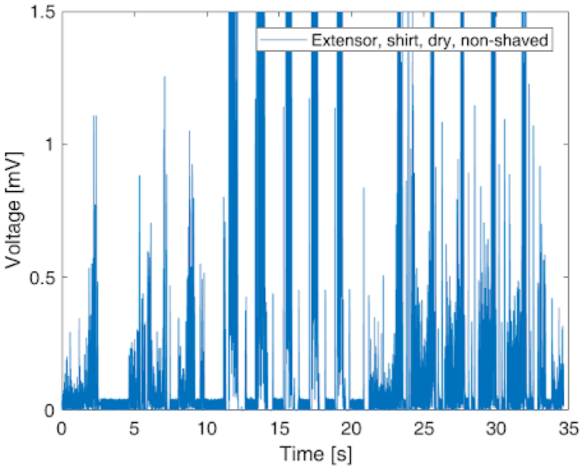

Fig. 4. Signal response of dry electrode on unprepared skin at the extensor mass

Signal response of the shirt with wet electrodes on unprepared skin at the pronator and the extensor

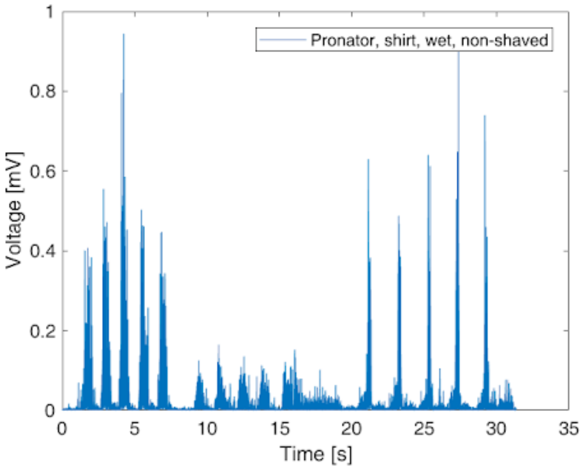

Fig. 5. Signal response of wet electrode on unprepared skin at the pronator teres

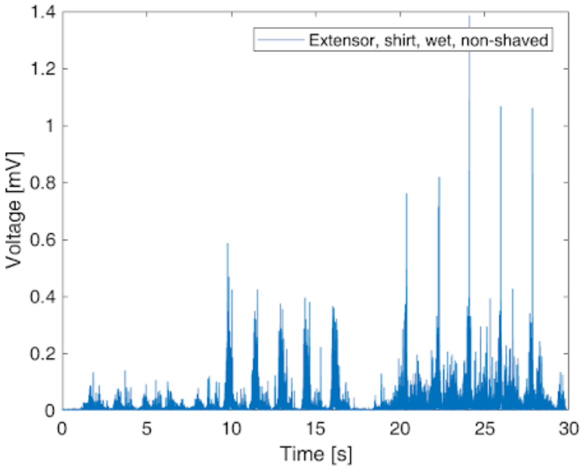

Fig. 6. Signal response of wet electrode on unprepared skin at the extensor mass

APPENDIX O

Displacement of the EMG sensor at the pronator teres and at the extensor mass

TABLE I

DISPLACEMENT OF THE PRONATOR

Pronator	**Dry 1 (mm)**	**Dry 2 (mm)**	**Wet 1 (mm)**	**Wet 2 (mm)**
Red to green	1.9	1.7	0.0	0.0
Green to black	1.6	1.4	0.8	0.7
Black to blue	0.0	2.2	1.3	0.0
Total displacement	1.9	1.7	0.0	0.0

TABLE II

DISPLACEMENT OF THE EXTENSOR

Extensor	**Dry 1 (mm)**	**Dry 2 (mm)**	**Wet 1 (mm)**	**Wet 2 (mm)**
Red to green	1.5	2.0	1.2	0.9
Green to black	3.4	1.4	0.9	1.1
Black to blue	1.3	1.0	0.7	0.5
Total displacement	6.2	4.4	2.8	2.5

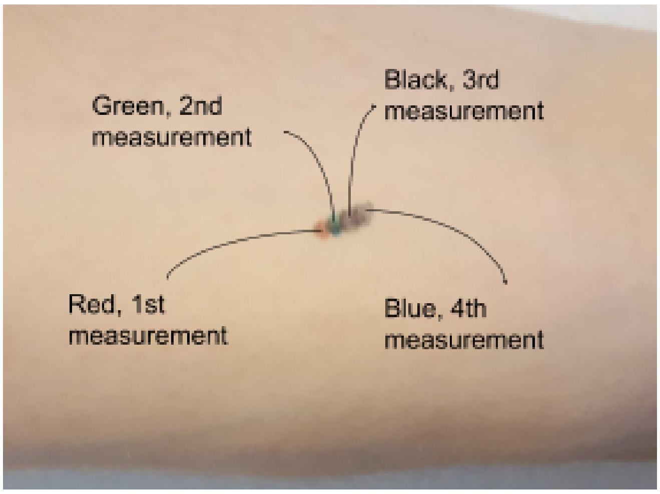

Fig. 1. The result of an experiment on the pronator teres

APPENDIX P

Test for user friendliness and robustness

Taking the shirt off was done by pulling the from the nek over the head and then the arms. Putting the shirt on was done by putting first the arms in the sleeves and then pulling the head through the neck of the shirt.

TABLE I

DISPLACEMENT OF THE EXTENSOR

Shirt	**Putting on (mm)**	**Taking off (mm)**	**Note**
1.	25.1	16.8	Connector between IMU wrist and wires disconnected.
2.	16.2	24.0	-
3.	20.0	25.2	Connector between IMU wrist and wires disconnected. EMG disconnected from hub.
4.	18.6	20.1	Connector between hub and wires upper arm disconnected.
5.	27.9	24.6	Connector between IMU wrist and wires disconnected.

TABLE II

COMFORT IN PUTTING ON AND TAKING OFF THE SHIRT

Comfort of taking off the shirt	**Scale of comfort shirt with equipment (1 to 5)**	**Scale of comfort shirt without equipment (1 to 5)**
Test subject 1	2	3
Test subject 2	1	4
Test subject 3	2	4

APPENDIX Q

Shirt sizes

For the different shirt sizes the following steps were conducted. To start off with, from a small database of baseball pitchers, the correlation between the arm length and height was calculated. The height plotted against the length of right arm yielded a R^2 value of 0.649 and the height plotted against the length of the left arm yielded a R^2 value of 0.688. This is found significant enough to assume a linear correlation with body height and arm length.

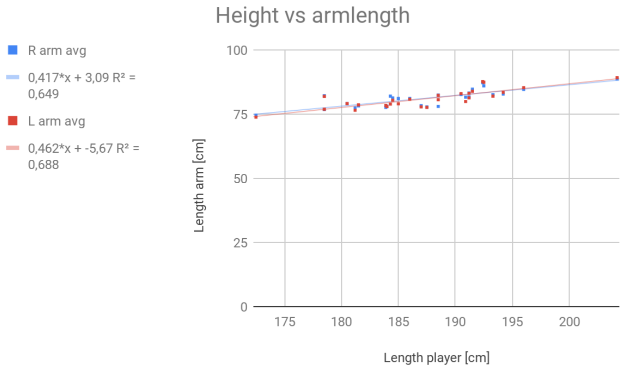

Fig. 1. The height plotted against the arm length

Secondly, the players from the database were subdivided in the categories S, M and L. The size S is made for people whose height is between 170 cm and 180 cm, similarly the M is for people between 180 cm and 190 cm and the L for people who are 190 cm tall or taller. The average arm length of the subgroups was calculated to be the following: for the S group the average arm length is 77.7 cm, for the M 79.3 and for the L 84.2. Standard ratios between height and length of body segments [30] were used to determine the ratio between hand, forearm and upper arm. Using these ratios and the arm lengths of the groups, the average forearm length of the different groups were calculated. The length of the forearm was calculated this way because the correlation between height and forearm length is not perfectly linear. Using arm length and the ratios of the arm takes into account different arm lengths.

Thirdly, the position of the pronator teres was determined using literature [9] saying its position is between 2 cm and 3.5 away from the midpoint of the epicondyle and the position where the bicep is attached to the elbow. Furthermore this position was also measured for the test user to be at around the same location. Since that user fits in the M category the EMG to measure the pronator teres is located at 3 cm from the previously described midpoint. Using this distance and the average forearm length of its group a ratio was calculated, pronator teres location over forearm length, and used to calculated the position of the pronator teres for the other groups. The location for the S group was calculated to be at 2.9 cm and for the L group at 3.2 cm.

Since the database of players was relatively small (three people in the S group, thirteen in the M group and 11 in the L group) and the average height of the S group was relatively high (177 cm) and the average height of the L group was relatively small (193 cm) the position of the EMG was respectively rounded off to 2.5 cm for the S group and to 3.5 cm for the L group. For the extensor mass, the same distances were calculated. This means the EMG should be located at 2.5 cm for the S, at 3.0 cm for the M and at 3.5 cm for the L.