Designing and developing a haptic feedback wearable to improve motor task performance: A case study on the squat

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Abstract

In this report the development of a haptic feedback wearable to improve motor task performance is described. Haptic feedback has many applications, including in the sports domain. In this case study the difference between haptic actuator placements and their influence on motor task performance was investigated. The difference between a localized and movement-specific feedback location and a more generic location on performance was tested using a squat as the motor task. For this purpose a wearable device that provides vibrotactile feedback on two areas of squat technique; squat depth, and contact of the heels with the ground, was designed. This wearable was then tested on 20 participants which were divided into two groups. For one group the haptic actuators were placed on the location of measurement, and for the other group they were placed on both wrists, simulating a pair of smartwatches. Based on the data from this experiment, no significant difference was found in performance between the two groups. Therefore, it can be concluded that in this specific application, placement of haptic actuators has no direct influence on motor task performance.

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Chapter 1

Introduction

It is clear how important general health and fitness is to our ever growing world population. Studies show that practicing some kind of sport or just moving more in general [1] reduces all kinds of diseases and improves quality of life significantly. However, over the past couple of decades our day to day lives have become more and more sedentary. According to the Centers for Disease control and Prevention (CDC), 25% of Americans spend 8 hours a day seated [2], This can also be seen in the development of motor skills in young children. Compared to 10-15 years ago, children of today are far less athletic [3]. So much so that according to Jac Orie, high level skating coach and MSc Human Movement Science, a random group of 30 children will generally produce 1-2 high level athletes where 15 years ago this would have been around 5 [4].

To counteract this trend incentives should be made for people to start moving more again, but this brings with it further complications. To get people moving in a safe and effective way, coaching is necessary. However, not everyone is in a position to hire a personal trainer and a quality personal trainer is hard to come by since everyone can register themselves as one [5].

Technology could help in solving this problem. Big companies like Apple are investing heavily in the smartwatch market. These devices lend themselves especially well for cardiovascular training like walking, running and cycling. These devices rely on haptic feedback to provide feedback to their users on their performance and fitness goals. An area where these wearables do not work yet, however, is complex motor tasks like weightlifting and strength focused sports in general. As research has shown, lifting weights is one of the best ways to stay healthy, acquiring stronger muscles is something that can help greatly in daily life and can for example also help the elderly to stay mobile and live at home for longer [6].

To develop wearable technology that can aid people in performing more complex motor tasks like weightlifting movements or muscle strengthening exercises with their own bodyweight without the need for a personal trainer, more research needs to be done on how to effectively provide feedback on these motor tasks. Haptic feedback technology as used in the before mentioned smartwatches can be used in such a piece of wearable technology to give feedback on more complex motor tasks than cardiovascular training. To provide useful haptic feedback to improve performance in a complex motor task like weightlifting, one of the things that should be investigated is the appropriate location for this feedback in the context of a specific movement.

The aim of this research is to explore how on a haptic feedback wearable, the placement of haptic actuators influences motor task performance of its users. The role that location specific haptic feedback plays in learning new motor patterns is an area of study that has not been fully developed yet. Research on this subject which will be elaborated on later in this report seems to hint at a more natural placement of actuators for a specific movement as the more optimal case as opposed to a more general placement of haptic actuators not unique to the current movement context. Improving performance in a motor task might be an indicator that motor learning is taking place. The research done in this report focuses on assessing whether actuator placement has an effect on performance, with the broader context of the use of haptic feedback wearables as a driver of motor learning.

The motor task that was chosen to test the effect of different actuator placements on performance is the squat. The squat is one of the most fundamental exercises in any strength training routine and one that involves every muscle in the lower body. This exercise also lends itself well to this kind of experiment, since it can be done without any equipment and in a relatively small space.

At the start of this research, a few preliminary research questions have been formulated. These questions are as follows:

Main Research question: What is the effect of localized versus generic feedback from a haptic feedback wearable on performance of a series of squats?

Secondary Research questions

1. What is the State of the Art of haptic feedback for motor learning?
   - What are comparable projects/products?
2. Which characteristics constitute correct squat technique?
3. How to design and develop a haptic feedback wearable to give haptic feedback on squat performance?
   - What sensors can be used to measure correct squat technique?
   - Can a machine learning algorithm be used on the device to analyze squat technique?

- Where can the actuators be placed in the localized feedback scenario?
- Where can the actuators be placed in the generic feedback scenario?

Chapter 2

Context analysis

This chapter presents a theoretical framework that forms the basis for the research in this report. To gain more insight into the background for this project, the subquestion: 'What is the State of the Art of haptic feedback for motor learning?' will be answered. Next to the literature research, a search was performed to answer the subquestion: 'What are comparable projects/products?'. After that, the squat was investigated with the subquestion: 'Which characteristics constitute correct squat technique?'. Then, the subquestions: 'What sensors can be used to measure correct squat technique?', 'Can a machine learning algorithm be used on the device to analyze squat technique?' and 'Where can the actuators be placed in the generic feedback scenario?' will be answered. The chapter concludes with a conclusion for these research questions and the formulation of a set of refined research questions used throughout the rest of this report.

2.1 State of the Art of haptic feedback for motor learning

2.1.1 Haptics

Haptic feedback can be defined as using the sense of touch in a human computer interaction context. [7]. This can be done using a variety of different techniques. Haptic feedback is commonly used in smartphones and gaming consoles to provide feedback to the user that is not visual or auditory in nature. This experience of touch can be achieved by many different haptic technologies. The most common are [8]:

Vibrotactile haptics : This technology uses (tiny) vibration motors to create tactile effects in mobile phones, game controllers and VR controllers. In this context these motors are mostly used on the hands (fingertips and palms). This can be a from of both active and passive touch.

Microfluidics : Smart textiles are used for transportation of air or liquid creating pockets of pressure or temperature felt on a users skin. This is a form of passive touch

Force control : Mechanical devices or levers are used to exert force on the body of the user. This is a form of active touch.

Surface haptics : Modulates friction between a users finger and a touch-screen to create tactile effects. Used to simulate textures or materials on a screen. This is a form of active touch.

2.1.2 Skill acquisition performance and motor learning

The research in this report will focus on increase in performance as a driver for motor learning. Direct motor learning will not be investigated, as this is beyond the scope of this project. Still, the process of motor learning lies at the base of this research. That is why the following sections will touch on previous research done on haptic feedback for motor learning.

Motor learning is generally defined as a set of processes aimed at learning and refining new motor skills through practice[9]. The process of motor learning consists of three main phases: cognitive, associative and autonomous. The cognitive phase is characterized by receiving instructions and continuously receiving feedback on performance.in this phase of the process, the amount of errors is usually high and performance varies. This is the phase with the most cognitive load. In the associative phase, the subject becomes more confident with the movement and the performance becomes less error-prone and more refined. When the subject reaches the autonomous phase, the motor task has becomes almost automatic and learning has taken place. The performance becomes fluid and the error rate will be very low. In the book Human Motor Control[10], David A. Rosenbaum argues that feedback aids skill acquisition, which in turn can lead to motor learning. He cites the closed-loop theory first coined by Adams [11], who argues that motor learning proceeds through the refinement of motor feedback loops. Feedback is given when a task is done incorrectly, gradually reducing the amount of errors made as practice continues. This feedback is known as knowledge of results, and usually people that receive knowledge of results will perform better than those that do not.

2.1.3 Haptic feedback for motor learning

In an exhaustive literature review by Sigrist et al. [12], the researchers review various forms of augmented uni-modal and multi-modal feedback: visual, auditory and haptic or a combination of these. In conjunction with this, the authors investigate the benefits of concurrent and terminal feedback paired with one or more of these three feedback modalities. In this review the researchers also stress the bidirectional properties of the haptic sense discussed above, which according to them enhances motor learning through haptic interactions. This is why the researchers deem it interesting to investigate the use of haptic interactions in motor learning. They raise a few important questions regarding this. Which haptic interactions enhance learning best? For what target group (beginners, experts, children, adults, etc.).

Feygin et al. argue in their research on haptic guidance in virtual environments that haptic feedback may aid in motor learning due to haptic feedback being better in training, which uses more body centered coordinates as opposed to visuospatial coordinates. This may help with complex skills that are hard to grasp from a visual or auditory explanation only. They also reiterate the fact that relatively little research has been conducted on examining haptic training, and the studies that have been done have failed to produce conclusive results. Haptic guidance guides the user through a complete motion, thus giving them kinesthetic understanding on how to perform this movement. In their research they combine this haptic guidance with visual training. They concluded that haptic guidance alone was less effective than visual training in areas of position and shape measures, but more effective in correctly timing the learned movement. What they did find is that when visual cues were present, the effect of the haptic guidance diminished. This led them to believe that vision somehow interferes with the haptic representation of the task the participants were given. [13]

Sigrist et al. [12] mention in their literature review that position control, a form of haptic guidance where a predefined reference movement is used to guide the user, may not be the most optimal way to use haptic feedback in motor learning applications. According to research by Scheidt et al. [14], motor learning took about 15 times as long when subjects were prevented from making errors as opposed to a situation where making errors was allowed. Position control systems prevent the user from making errors. However, they state that for beginners or less skilled users who do not know the movement, position control may be useful. Position control for the facilitation of motor learning has rarely been tested. It may be very helpful in the early stages of learning complex movement patterns and may help in acquiring a first movement representation. This conclusion by Sigrist et al. may make position control an interesting option to consider in this project, since they state the potential of this technology has not really been researched in a motor learning context, and could be helpful to first time trainees. Furthermore, they state that position control is mostly useful in an instructional context at the beginning of the learning phase.

2.1.4 Concurrent vibrotactile feedback systems

According to Sigrist et al. [12], vibrotactile feedback systems need to be evaluated in motor learning. Vibrotactile feedback has been studied in many diverse sports contexts, but research on motor learning using vibrotactile displays is rare. A 2009 study by Ruffaldi et al. [15] Used a virtual environment to train rowing. This virtual environment used a visuo-vibro-tactile feedback system to provide feedback to the user. This consisted of a large screen and vibrotactile bracelets for guidance or error feedback. The system gives concurrent haptic feedback when a user makes an error while performing the rowing task. The preliminary conclusion of this research is that a combination between both vibrotactile feedback and visual feedback leads to more transfer than only visual or vibrotactile feedback. This is of course a very minimal result and does not give much concrete evidence that concurrent vibrotactile feedback is beneficial or detrimental for motor learning purposes. It does however imply that a multimodal feedback strategy may be useful in this specific case. As Sigrist et al. also mention, designing a practical and meaningful vibrotactile feedback system is challenging. Placement of the actuators and strength of vibrations are difficult to get right.

A 2011 study by Van der Linden et al. [16] used a vibrotactile feedback suit during an in the wild study to look at the effects of vibrotactile stimuli on children learning to play the violin over a 2 month period. The study was mainly focused on two skills: Holding the violin in an upright position and straight bowing (moving the bow of the violin in a straight line forwards and backwards across the violin). The movements of the students were tracked with a motion capture setup and real-time corrective vibrotactile feedback was provided. Holding the violin upright saw the most improvement while using the vibrotactile feedback system. This is likely because it is a simple motion and does not influence playing the violin all that much. The researchers note that the haptic feedback can make a task more difficult for the student. Long term learning effects after the haptic feedback system was not used anymore have not been observed in this study.

2.1.5 Feedback location

According to Sigrist et al. [12], appropriate sites on the body must be found to apply vibrotactile feedback. The vibration must be easy to perceive and the motors should not hinder movement. They argue that some sites might have an advantage over other sites in respresenting specific information about movement. This might be due to the naturalness of the site in correlation with the movement.

Wrist-based haptic feedback devices are currently the most pervasive form of wearable haptic feedback devices. According to Statista[17], the global revenue of the activity tracking wristwear market was $16.1 billion in 2022 and is expected to grow to $32 billion by 2027. This makes the wrist the most used location for providing haptic feedback on fitness and activity.

In a 2011 study by Stepp and Matsuoka [18], 18 unimpaired participants were asked to manipulate a virtual object with their index finger using a robotic interface with visual and vibrotactile feedback. They received this vibrotactile feedback each at four sites (finger, arm, neck, foot) on the body in a random order. Initially, the finger location seems to offer an advantage compared to the other locations, but this fades quickly when users have more time to learn to interpret the feedback.

In a study by Mikula et al. [19], the researchers asked participants to blindly reach for the index finger of their left hand with their right hand. They provided a vibrotactile stimulus to the target index finger prior to starting the movement. Participants made smaller errors and more consistent reaches for the index finger following this vibrotactile stimulus. When providing the same vibrotactile feedback on the shoulder instead of the index finger, such improvements were not observed. The researchers argue that there is a specific spatial integration of touch and proprioception when performing such movements, where touch at a relevant body location provides improved position sense.

A paper by Jan van Erp[20] tested a rowing setup in which 3 different types of feedback were given to the participants. The participants received feedback on whether and how much their back their back was too early or too late during the pulling phase of a rowing stroke. A sample of 22 female rowers were randomly divided into three feedback groups. Group 1 received haptic feedback with a vibration motor on the back and one on the knees. These motors gave direct feedback when a certain knee or back angle was reached. Group 2 received visual feedback on a screen in front of them. The nature of the feedback was the same, only on a different location and modality. Group 3 received delayed, non-positional feedback. They received feedback on every stroke, but only after 25 strokes. This feedback was also given on a visual display just like for group 2. The effects of these three different feedback strategies were measured on 3 different variables: timing (difference in ms between reaching the set knee angle and set back angle), heart rate and speed in km/h. No significant differences were found between the three groups in timing and speed. Heart rate was significantly lower in the post test compared to the pre-test for group 1, who received positional direct haptic feedback. The researchers argue that a very high performance level can be maintained with lower effort when receiving tactile feedback.

2.1.6 Comparable projects/products

Next to the literature research, a search was also performed to find existing products or projects that aim to tackle similar problems as described in this report. A project that does exactly the same as the prototype developed in this report was not found however. Products were found that leverage haptic feedback in an interesting way or that analyzed squat technique. This gathered information was mostly used to aid in the ideation phase of this project.

VMaxPro [21] is a sensor that can be placed on any standard Olympic barbell. With an accompanying app it can be used to analyze bar path, velocity and force production during barbell exercises. The company claims that through this velocity based training approach it can give an accurate representation of fatigue levels and customize training based on this. It offers no on-body sensors or actuators and only provides terminal feedback on training performance in the accompanying app.

The balance belt [22] is a vibrotactile wearable belt developed by Elitac Wearables in collaboration with the Maastricht university hospital. This belt allows patients suffering from sever balance disorders to find balance and regain their independence. It provides vibrotactile feedback via the waist at 12 different zones when the trunk sways out of position. 23 out of the 31 participants in this study indicated a clear benefit in daily life. There is however no learning effect. This wearable is only effective when it is being worn.

TIKL [23] is an abbreviation for tactile interaction for kinesthetic learning. It is a proposed robotic wearable suit able to apply real-time corrective vibrotactile feedback to a user following instructions from a teacher performing said movement simultaneously. a visual motion tracking system tracks the movement of the teacher as well as the student. When a joint of the student moves erroneously, the suit will give vibrotactile feedback proportional to the amount of error. Only tested with movements of the right upper arm.

Squat Mate [24] is a prototype for a wearable device to improve squatting created by Grace Yuan of OCAD University. The device focuses on sensing squat depth and giving feedback via LED lights on the device. The device is worn on the upper leg so the LEDs are not in the direct field of vision of the user. The creator also claims squats below 90 degrees put too much strain on the knees and should be avoided. When this happens the red LED turns on.

2.2 The Squat

2.2.1 Importance of the squat

The squat is one of the most fundamental exercises in any (weight)training program. It mimics a natural movement and is indicative of proper mobility. In our western society, the practical use for the squat has greatly diminished over the years, but in other countries and cultures the squat movement is much more common. In some cultures the bottom position of a squat is used as a means of sitting down because there are no chairs available. However, the squat still strengthens many of the lower body musculature used in daily life. Because people in western societies tend to be sitting the majority of the day, most of us are not able to get into a proper squat position. This is due to the fact that sitting for repeated long periods of time shortens the hip flexor muscles and weakens the glute muscles [25]. This makes it almost impossible for some people to get into a deep enough squat. The squat is a highly versatile excercise that has both performance and rehabilitation purposes. The squat effectively strengthens the entire lower limb musculature which can help in improving sports performance but also activities of daily living (ADLs). Simple bodyweight squats improve the performance of ADLs in older individuals and can help mitigate age-related conditions such as sarcopenia (muscle loss in older adults). This prevention of muscle atrophy can in turn reduce fall risk. [26].

2.2.2 Importance of correct technique

For optimal activation of the quadriceps and gluteus muscles, it is advised to squat at least until the upper leg is parallel to the floor [27]. Squatting higher than this does not provide the same amount of stimulation to the prime movers of the exercise. Activation of the gluteus muscles seem to be the highest when squatting until the upper leg is at least parallel with the floor[26]. Squatting on an unstable base impairs the amount of force and power that can be produced in the prime movers of the squat, thus leading to a less effective muscular stimulus.

2.2.3 Muscles worked

The major muscle groups worked in the squat are the gluteus maximus (largest portion of hip musculature) and the quadriceps. Due to the squat being a free standing exercise, many secondary and stabilizing muscles also come into play, most notably the hamstrings, calves, spinal erectors, inner thigh muscles and abdominal muscles.

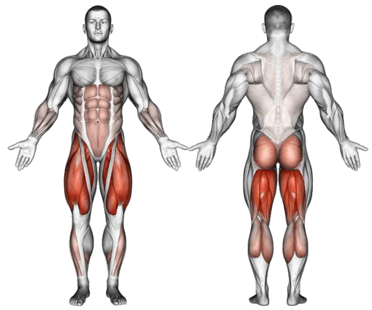

Figure 2.1: Muscles worked in a squat, Source: fitnessvolt.com

2.2.4 Correct technique

As per the National Academy of Sports Medicine (NASM) [28], a correct squat should be performed as follows:

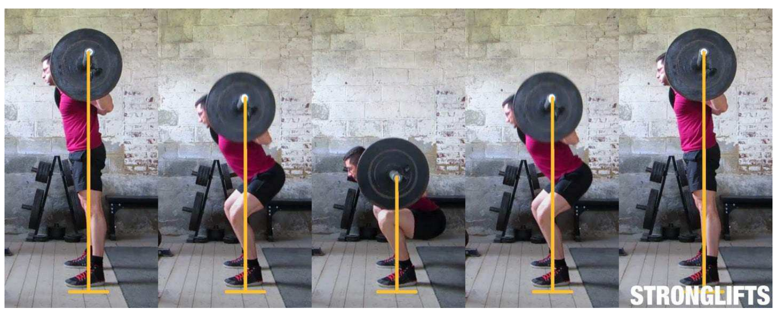

Figure 2.2: Proper squat technique, Source: stronglifts.com

- Slowly begin to squat down by hinging at the hips and then flexing at the knees.
- Allow glutes to stick out behind the body as if sitting into a chair.
- Keep the chest up and the cervical spine in a neutral position. Avoid excessive cervical flexion, extension, or anterior translation (jutting the head forward).
- Squat to a depth that can be safely controlled with no movement compensations.
- To rise back up, contract the gluteals and place pressure through the heels as the knees and hips are extended.
- Stand up straight until hips and legs are fully extended. Fully contract the gluteals in the standing position for maximal muscle recruitment.

2.2.5 Common errors in technique and misconceptions

Squat depth How deep a squat should be is a highly discussed topic in the fitness community. Some teach a squat to a depth in which the upper leg (femur) is parallel to the ground, Others only consider ”full” squats (below parallel) as a real squat. Then there is also a small group that believes even squatting to parallel can be detrimental for one's knees. It appears that squats to parallel produce the best results in terms of quadriceps development [29]. Going deeper will lead to little gains in hip muscle activation. For the general population it is advised to squat to parallel if a person's joint mobility allows this. According to a 2019 study by Pallares et al. [30], full squats and parallel squats produce greater neuromuscular adaptations than half squats. Where full squats and parallel squats improved strentgh and functional performance, half squats did not improve performance, but did lead to significant increases in pain, stiffness and physical functional disability. In a literature review by Clark et al. [27], the researchers found no difference in muscle activation of the prime movers in a squat measured by electromyography (EMG) between a parallel squat and a full squat. It appears that activation is greatest in the last part of the descent to parallel and the first part of the ascent.

Knee valgus According to the NSAM [28], the most common movement compensation pattern in a squat is knee valgus, also known as medial knee displacement or 'knock knees'. knee valgus can occur when there is not enough strength or mobility in the muscles below or above the knee, namely the ankle or hip. This can be limited ankle mobility and weakness of th hip abductors and external rotators. Some experts argue that knee valgus (to a certain extent) is not as harmful as was previously assumed. This can be seen in the biomechanical differences between males and females. The fact that females mostly have wider hips than males results in a larger so called 'q-angle'. This can lead to more knee valgus while squatting in female trainees. This can be seen in Figure 2.5.

Heels coming off of the ground According to a study performed by Myer et al. [31], when the heels are raised off the ground during a squat this puts extra compensatory torque on the ankles, knees, hips and lumbar spine. The heels coming off the ground also leads to a less stable base and less surface area for support, reducing the athlete's ability to perform a balanced and controlled squat. This may then in some cases lead to serious injury. In a literature review by Clark et al. [27], the researchers conclude that instability impairs force and power production during a squat, reducing the external load that can be used for the exercise. A higher external load leads to increase in activation of the muscles of the legs and trunk.

Harmful forward knee travel Despite many published papers on this topic, it is still a widespread belief of many personal trainers and gym goers worldwide

Figure 2.3: Heels on the floor during a squat

Figure 2.4: Heels off the floor during a squat

that during a squat the knees should not travel past the toes. This would endanger the knees and create all sorts of problems later down the line. This section shows a study that proves this common myth wrong.

In a 2003 study by A.Fry et al. [32] a group of 7 weight trained men were asked to perform two forms of squats to measure torque on the knee joint and hip joint. The first variation was an unrestricted squat where the knees were allowed to travel past the toes, while in the second variation a wooden board was placed against the toes of the participants as can be seen in figure 2.6, restricting the forward movement of the knee. It was found that while in the unrestricted squat torque on the knee was slightly higher than on the restricted squat (150 Nm vs. 117 Nm), the torque on the hip joint was significantly lower in the unrestricted squat (28 Nm) than in the restricted squat (302 Nm).

Points of interest in technique In this project a haptic feedback wearable will be designed to help with improving performance in the squat. These previous sections show that there are certain points of interest in squat technique where such a wearable could help. The most interesting point would be tracking heel position and squat depth. Such a device could give its users feedback when the heels have lost contact with the ground during a repetition, and if the user has squatted to the correct depth or not.

2.3 Expert opinion

To gain more information and knowledge about the topic of teaching the squat and coaching in general, an interview, approved by the ethics committee at the Univeristy of Twente[1], was conducted with Lars Giesen, coach at Bespoke

[1]Reference number RP 2021-218

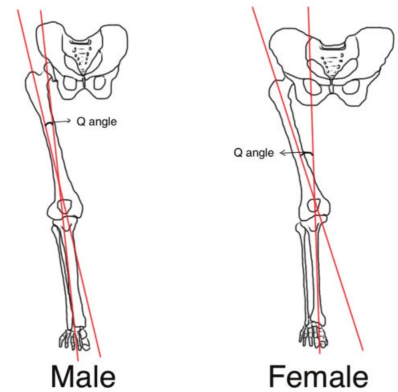

Figure 2.5: Male vs. female Q-angle

Strength[2]. They offer (online) coaching to individuals that want to take their strength training to the next level. He reiterates that they mostly work with people that already have experience in the gym, mainly powerlifters, people that train for muscle hypertrophy (gaining muscle mass), and people that train for general fitness (losing fat, gaining muscle, staying healthy). Most of his athletes practice the squat in their training programs. For his clientele practicing (competitive) powerlifting he uses the squat to let them get more skilled in the movement as they have to perform it for their sport. for his more regular clients he mainly uses the squat to let them gain muscle tissue in their quadriceps and glute muscles. When asking him about the aspects he looks for in his clients while squatting he sums it up like this:

- Unracking the loaded barbell from the squat rack: Does the client produce enough active tension with their back against the barbell, allowing it to rest securely on the back?
- Before starting the squat: Are the knees locked and is the torso upright? This is mostly for powerlifting clients as this is required in competition. It is also good practice to learn your squat this way even if you do not powerlift.
- Starting the repetition: Does the athelete brace their core and generate tension through the lats (latissimus dorsi, outer muscles of the back)?
- Bar path: During the repetition the barbell should move in a (mostly) vertical line over the mid-foot. If this is not the case, there is an energy leak somewhere in the kinetic chain.
- Depth: For powerlifting it is important that the hip joint is lower than the knee joint before coming up again. This is roughly the same as having the upper leg parallel to the ground, but in powerlifting this is judged

[2]https://www.bespokestrength.nl/

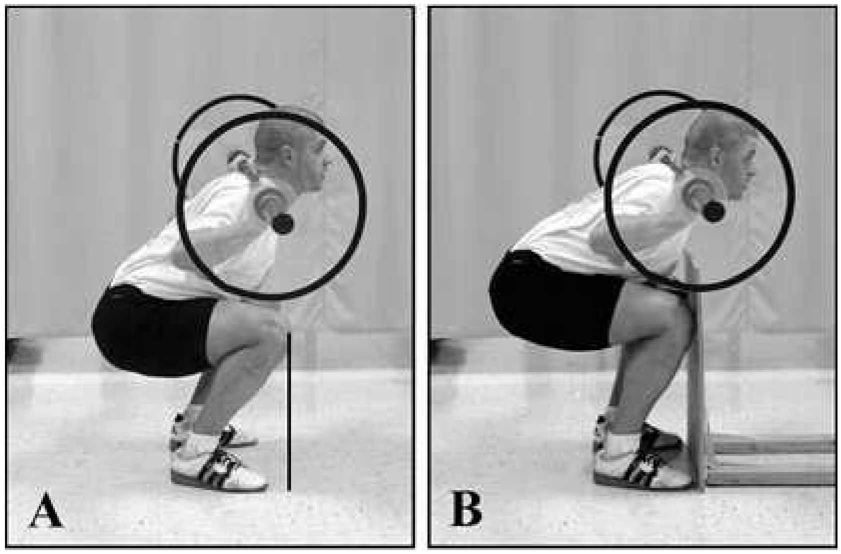

Figure 2.6: Forward knee travel in a squat

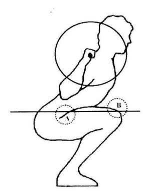

Figure 2.7: Depth of a squat for powerlifting

based on the 'hip crease' in relation to the knee(see figure 2.7). For clients looking to optimize their quadriceps development he is mainly looking for as much knee flexion as possible to optimize quadriceps activation.

- Coming up: When coming up again from the lowest point in the squat, The hips should not shoot up too quickly and the knees should not go backwards too early. Both joints should move together in synergy to propel the upper body upwards again in a fluid motion.

Before joining Bespoke Strength, Lars has also worked as a personal trainer in a gym. During this time he has also trained more inexperienced athletes to squat. When asked to describe a good squat, he mentions that for him it mainly consists of three things: Stable feet, consistent and deep enough depth throughout the set, and providing active tension throughout the movement. He argues that knee valgus and a 'perfect' back angle are not really big points of interest for him. Only when these symptoms get too extreme, e.g. the knees touching or excessive rounding of the spine, you should start to look for the cause. His take home message is that every person's body composition is different and thus every squat will also look different. He thinks it would be interesting to look at consistency of squat technique during a set or over multiple set. When training with heavier loads or when training close to muscular failure it is not uncommon to see technique break down. Giving feedback when the technique starts to break down could be a good way to ensure it does not break down any further.

2.4 Technology exploration with the MPU-6050 and TinyML

To gain more insight into the workings of an Inertial Measurement Unit (IMU) as a sensor to measure one of the aspects of correct squat technique and to answer the subquestion: 'Can a machine learning algorithm be used on the device to analyze squat technique?', a small project was carried out. The goal of this project was to build a device that can detect different motions like forward movement, sideways movement, and movement in a circle. The IMU that was chosen is the MPU-6050. This is a low-cost 6-axis gyroscope and accelerometer. This sensor is readily available and also comes standard with many Arduino starter kits. To interface with the IMU from a microcontroller the MicroPython language was used in conjunction with TinyML. MicroPython is a version of the Python programming language specifically developed to run on various kinds of microcontrollers. TinyML[33] is broadly defined as machine learning technologies running on-device sensor data analytics at very low power requirements, thus enabling machine learning algorithms to run on battery powered devices with low power budgets and compute power. TinyML algorithms can be programmed on a microcontroller using Micropython without using external libraries.

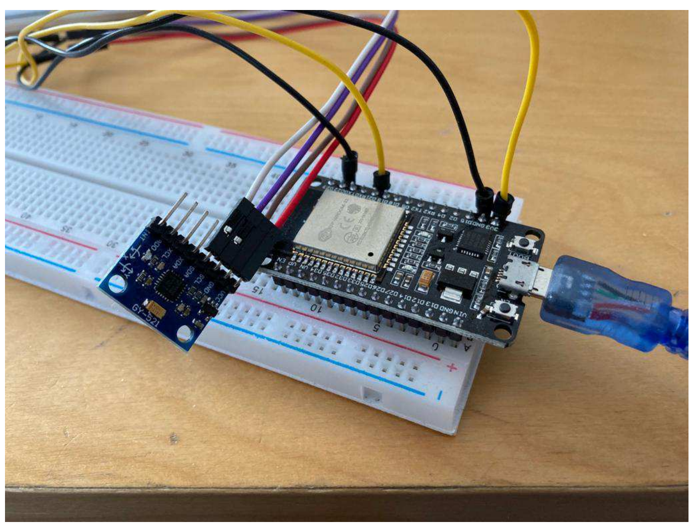

Figure 2.8: ESP-32 with an MPU-6050 gyroscope/accelerometer

In figure 2.8 the setup that was used can be seen. This project was relatively short, but many new insights were gained about micropython on the ESP-32 microcontroller and the MPU-6050 Inertial Measurement Unit (IMU). Having previously only worked with ESP boards using the Arduino programming language based on C++ in the Arduino IDE, working with micropython was quite a big change. The setup process was not as straightforward and there is no dedicated development environment specifically for MicroPython. This makes it a little more difficult to use in a prototyping phase where code has to be uploaded to the microcontroller many times. This meant that the setup for this small project took longer than was initially expected. Eventually somewhat of a development environment had been set up in which code for the project could be worked on.

There was no driver available written in MicroPython for the specific IMU used in this project, so parts of a driver for a somewhat similar one had to be rewritten instead. This sums up working with MicroPython in this project. Eventually some code was able to be run and the values that the MPU-6050 was producing could be read. Overall, the benefits of being able to work with Python on a microcontroller did not outweigh the negatives of a slow workflow and a far inferior development community for MicroPython compared to programming development boards using the Arduino programming language and its IDE. The MPU-6050 also has a larger user base in the Arduino IDE community. Multiple libraries to interface with the sensor are available which can be easily integrated in a project. This is why during the remainder of this project the Arduino IDE was used to develop all of the necessary code for the wearable device.

Implementing a machine learning algorithm on the ESP-32 with Micropython proved to be quite a struggle as the lack of a dedicated development environment made it quite hard to interface with the device and prototype. This means that the costs of implementing such a machine learning algorithm far outweigh the benefits. The sensor data coming from the IMU can be analyzed without the use of machine learning, especially for a movement such as the squat. To use the IMU for measuring the depth of a squat, only the angle of one axis from the IMU has to be analyzed. The use of machine learning in this case would be quite excessive and would only add extra development time to the project. Therefore, the use of a machine learning algorithm will not be pursued further in this project.

2.5 Conclusion

In this concluding paragraph of the context analysis, a few of the preliminary research questions are answered, and more definitive ones are formulated.

2.5.1 What is the state of the art of haptic feedback for motor learning?

From the state of the art on haptic feedback for motor learning it becomes clear that although there are many forms of haptics, vibrotactile feedback seems to be the most common among studies in the field on motor learning. Here it also becomes clear that the general question: "How can haptic feedback support motor learning?" is quite difficult to answer. Research on haptics for motor learning - and especially in sports - is scarce. Most of the science focusing on motor learning applications for haptics researches movements not necessarily associated with sports training. In the few studies on sports applications that have been done the results were mostly inconclusive on the benefits of haptic feedback. The studies mentioned in this report do show that there is potential for haptics in the realm of motor learning. This means that the current project can add real value to the research body on haptic feedback for motor learning applications.

2.5.2 What are comparable projects/products?

In the section on comparable projects there are several products that focus on improving various parts of the squat. What these products lack however is on body sensing (VMaxPro), or haptic feedback (Squat Mate). The other two projects are interesting applications of haptic feedback, but one (the balance belt) does not offer any learning effect, while the other (TIKL) is quite an intrusive piece of technology which so far has only been used to give corrective feedback on movements of the upper arm. The wearable proposed in this report seems to offer some unique qualities not seen in any of the comparable projects.

2.5.3 Which characteristics constitute correct squat technique?

From the section on squat technique it has become clear that the line between correct and incorrect technique is not as clear as was once believed. There also seems to be no such thing as a 'perfect' squat, as technique varies based on proportions and leverages of the individual performing the exercise. This makes it harder to find points of interest where a wearable device could aid in correcting technique. From the interview conducted with a strength coach it becomes clear that consistency across a whole set of squats is one of the most important factors in determining if squat technique is good. Two areas of interest to measure this consistency mentioned in the report are tracking heel contact with the ground and correct depth. Even though there is no such thing as a perfect squat for all individuals, these two modalities should be consistent across all trainees. From the literature it seems that muscle activation of the prime movers during the squat (quadriceps and gluteus muscles) is highest when squatting to at least parallel, while the ability to output enough force is directly related to a stable footing during the squat. More force production in the squat means that higher external loads can be used, increasing the activation of the lower body musculature. That is why these are the characteristics of squat technique that will be focused on during this project.

2.5.4 What sensors can be used to measure correct squat technique?

As mentioned in the previous section, the modalities that will be focused on are squat depth and heel contact with the ground. The squat depth can be measured via the use of an Inertial Measurement Unit (IMU) such as the MPU-6050. The heel contact with the ground can be measured with a pressure sensor on the heel. This also leads to the formulation of the research question: "Where can the sensors to measure correct squat technique be placed to ensure correct measurements?". The usage and placement of these sensors are explained more in-depth in the following chapters of this report.

2.5.5 Can a machine learning algorithm be used on the device to analyze squat technique?

During the small project that was done to experiment with Micropython and TinyML on a microcontroller it was found that deploying a machine learning algorithm on such a device is not straightforward. The benefits of machine learning in the context of this project is also predicted to be minimal. This means that even though machine learning on low power devices such as microcontrollers is a very exciting technology, it is of no real benefit in this project and will therefore not be implemented.

2.5.6 Where can the actuators be placed in the generic feedback scenario?

Smartwatches and wrist-worn activity trackers are a rapidly growing market. Many people today are already wearing some kind of smart watch or wrist-worn device capable of haptic feedback. Therefore, for the scenario where vibrotactile feedback will be delivered on a movement a-specific location on the body, the wrists are the most appropriate location.

2.5.7 Refined research questions

This leads to the formulation of refined research questions and sub-questions that will be answered in the next phase of this project. The main research question still stands, although haptic feedback has now been changed to vibrotactile feedback. The reasoning for this is that it is the most applicable form of haptic feedback in the context of this project.

Main research question What is the effect of localized versus generic feedback from a vibrotactile feedback wearable on performance of a series of squats?

Secondary research questions

1. How can sensors be used to measure the two chosen indicators of correct squat technique?
    - How can Inertial Measurement Units (IMU) be used to measure depth during a squat?
    - How can a pressure sensor be used to measure heel contact with the ground during a squat?
    - Where can the sensors to measure correct squat technique be placed to ensure correct measurements?
2. Where can the vibrotactile actuators be placed in the localized feedback scenario to provide comfortable, effective and intuitive feedback?
3. How to evaluate the effectiveness of the wearable?

Chapter 3

Methodology

3.1 Aim of the research

To investigate the influence of different placements of vibrotactile feedback actuators on motor task performance, two different parameters of correct technique in a squat were tested. The two parameters of the squat that were used are squat depth and heel contact with the ground. For each of the tested parameters, two feedback locations were chosen, one body and movement specific location and one a-specific generic location. For the body a-specific actuator placement the wrists were chosen. As mentioned in the introduction and context analysis, smartwatches are often used to monitor sports performance. Placing the actuators on the wrist of a participant simulates the feel of a smartwatch providing haptic feedback.

In this chapter the methods used throughout the following chapters of this report are laid out. First, an experiment was done to determine the placement of the vibrotactile actuators in the localized feedback scenario. After this, the optimal placement of the sensors to accurately measure the two parameters of squat technique was investigated. Then, the assembly of the final prototype of the wearable is discussed. Finally, an evaluation test was done to test the effect of different actuator placements on squat performance.

3.2 Experiments

3.2.1 Experiment on vibration motor placement

To answer the question: **'Where can the vibrotactile actuators be placed in the localized feedback scenario to provide comfortable, effective**

and intuitive feedback?', an experiment was done. This experiment can be found in chapter 4. In this experiment the locations for the body specific actuator placements were chosen. four participants were asked to rank 3 different actuator placements for each squat parameter on comfort, vibration strength and intuitiveness. Intuitiveness was chosen as a category to represent the naturalness of the location compared to the squat parameter that was tested. So for the parameter squat depth, intuitiveness represents the placement that corresponds most to that specific movement for that participant.

Participants for this experiment were a small convenience sample of 4(2 male, 2 female).

3.2.2 Experiment on sensor placement to measure squat depth

To answer the question: **'Where can the sensors to measure correct squat technique be placed to ensure correct measurements?'**, an experiment was done using the proposed placement of the squat depth sensor, to measure if squat depth was correctly measured over the length of a series of squats. This experiment can be found in chapter 5. The experiment was performed on the researcher, who squatted to correct depth for 3 sets of 10 repetitions. when correct depth was reached according to the sensor, a picture was taken with a camera standing on a level surface. These pictures where then overlaid to see if the measurements were consistently correct over the series of squats.

3.2.3 Evaluation test

To answer the question: **'How to evaluate the effectiveness of the wearable?'**, an evaluation test was performed. This evaluation test can be found in chapter 7. The evaluation test consisted of 20 participants with no prior squatting experience being asked to perform 3 sets of 10 squats each while wearing the wearable device. The research population was split up into two groups of 10 resulting in a between subjects design. The research population consisted of people between the ages of 20-30, with a 50-50 split of males and females in both groups. The first group received body-specific feedback on their squatting technique. For squatting depth, feedback was given on the front of the upper leg. For heel contact with the ground, feedback was given on the back of the ankle. The second group received body a-specific feedback during their sets of squats. This feedback was given on the right wrist for squat depth, and on the left wrist for heel contact with the ground. After a time interval of a week, the experiment was run again in the same fashion with the same research population and same groups. This was done to see if there would be any difference or improvement between the two sessions. After each session, participants were asked to fill out a copy of the NASA TLX questionnaire to subjectively rate their performance.

Data from both the squat depth sensor and heel pressure sensor were logged and saved for each participant. This data was later used to perform data analysis to see if there was any significant difference in performance between groups and sessions. Statistical analysis was done using a Mann-Whitney U test. This is a non-parametric test, which was necessary because the gathered data did not satisfy all the constraints needed for a parametric test. The null hypothesis of the Mann-Whitney U test states that there is no difference in distribution between the two samples that were tested. This leads to the following hypotheses:

- ***h0***: The distributions of the two groups are the same
- ***h1***: The distributions of the two groups are different

3.3 Wearable development

The wearable was developed in incremental fashion using an iterative method containing aspects from the Design Thinking method (Ideate, Prototype, Test). This happened in conjunction with the experiments on actuator placement. The development phase was split up in ideation, prototyping and testing. Multiple prototypes were developed. This process is further elaborated on in chapter 6. The sensors that were chosen to measure characteristics of a correct squat were then benchmarked against a ground truth to make sure the measurements are correct. This benchmarking process is also described in more detail in chapter 6

Chapter 4

Vibration motor placement

In this chapter the subquestion: 'Where can the vibrotactile actuators be placed in the localized feedback scenario to provide comfortable, effective and intuitive feedback?' will be answered using a small experiment.

4.1 Experiment on motor placement

4.1.1 Method

To figure out where the motors for the final wearable prototype need to be placed, a small experiment was carried out. In this experiment four participants were asked to rate different placements for vibration motors on comfort, vibration strength, and intuitiveness. Intuitiveness is defined as a subjective ranking how the participants felt this feedback location correlated with the squat mechanic they were performing. This experiment was inspired by a similar experiment performed by De Graaf [34] to find the optimal placement of vibrotactile actuators to improve posture during inline skating.

For the first part of this experiment the participants were asked to perform squats to non-adequate depth, after each repetition they would receive feedback on one of the vibration motors. for the depth vibration motor the different positions were: Front of the upper leg, front of the knee, and side of the upper leg. The participants wore a version of the wearable with 3 vibration motors attached. These motors were housed in a 3D-printed casing which was attached to a velcro band so the motor could be easily attached and detached when te experiment was over. The participants were fitted with the wearable and the vibration motors, and were then instructed to do six squat repetitions, so that each vibration location could be felt twice. After this they were asked to rank all three locations on comfort, vibration strength and Intuitiveness.

For the second part a similar experiment was carried out but this time for the motors giving feedback on the heel position during the squat. For this experiment 3 locations for the vibration motors were chosen again. Since the position where the sensor would be attached in the final prototype (the heel) is not suitable to place a motor, 2 positions (outside and back) on the ankle were chosen, as well as the back of the lower leg. Similarly to the first experiment, participants were asked to perform six repetitions of a squat, so each vibration motor would be felt twice. In this case the participants were instructed to lift their heel off the floor somewhere during their squat repetitions to simulate a motor being triggered.

4.1.2 Results

4.1.3 Squat depth motor placement

The rankings for each motor position can be seen in table 4.1. As can be seen in the table, all participants unanimously chose the front of the upper leg as the most comfortable place for the vibration motor. The knee seems to be the least comfortable position. Participant 2 noted that during the squats, the motor would not stay in place and would slide down, making it uncomfortable to wear. All participants said that a vibrating pulse on the knee joint was also not very comfortable. Vibration strength was rated highest on the front of the leg or on the knee. Here participant 2 ranks the knee lowest because of the sliding off of the motor. For Intuitiveness all participants ranked the front of the upper leg the highest. The ratings here almost completely coincide with the rankings for comfort, except for participant 4, who commented that the motor on the side of the upper leg felt like a signal for a lateral movement of the leg rather than a vertical movement. Based on these ratings, the front of the upper leg was ultimately chosen as the position for the vibration motor that gives feedback on squat depth.

4.1.4 Heel position motor placement

The rankings for each motor position can be found in table 4.2. For this experiment the data is not as overwhelming in pointing to one obvious motor placement as it was for the squat depth motor placement. However, 3 participants mentioned that the vibration on the outside of the ankle was not very comfortable, because it was right on the bony part of the ankle. Vibration strength was ranked similarly across the back and side of the ankle. This was also true for intuitiveness. Here the position on the back of the leg was considered to be the least intuitive. One participant noted that they did not associate a vibration on the back of their lower leg with an action of their heel. Ultimately the back of the ankle was chosen as the place for the heel position vibration motor, mainly

Participant	Comfort	Vibration strength	Intuitiveness
1	1. Front leg 2. Side leg 3. Knee	1. Knee 2. Front leg 3. Side leg	1. Front leg 2. Side leg 3. Knee
2	1. Front leg 2. Side leg 3. Knee	1. Front leg 2. Side leg 3. Knee	1. Front leg 2. Side leg 3. Knee
3	1. Front leg 1. Side leg 2. Knee	1. Knee 2. Front leg 3. Side leg	1. Front leg 2. Side leg 3. Knee
4	1. Front leg 2. Side leg 3. Knee	1. Front leg 2. Knee 3. Side leg	1. Front leg 2. Knee 3. Side leg

Table 4.1: Ranking for the placement of the squat depth vibration motor

Participant	Comfort	Vibration strength	Intuitiveness
1	1. Side ankle 2. Back ankle 3. Back of leg	1. Back ankle 2. Side ankle 3. Back of leg	1. Back ankle 2. Side ankle 3. Back of leg
2	1. Back ankle 2. Back of leg 3. Side ankle	1. Side ankle 2. Back of leg 3. Back ankle	1. Side ankle 2. Back ankle 3. Back of leg
3	1. Back of leg 2. Back ankle 3. Side ankle	1. Back ankle 2. Back of leg 3. Side ankle	1. Side ankle 2. Back ankle 3. Back of leg
4	1. Back ankle 2. Back of leg 3. Side ankle	1. Back ankle 2. Side ankle 3. Back of leg	1. Back ankle 2. Side ankle 3. Back of leg

Table 4.2: Ranking for the placement of the heel position vibration motor

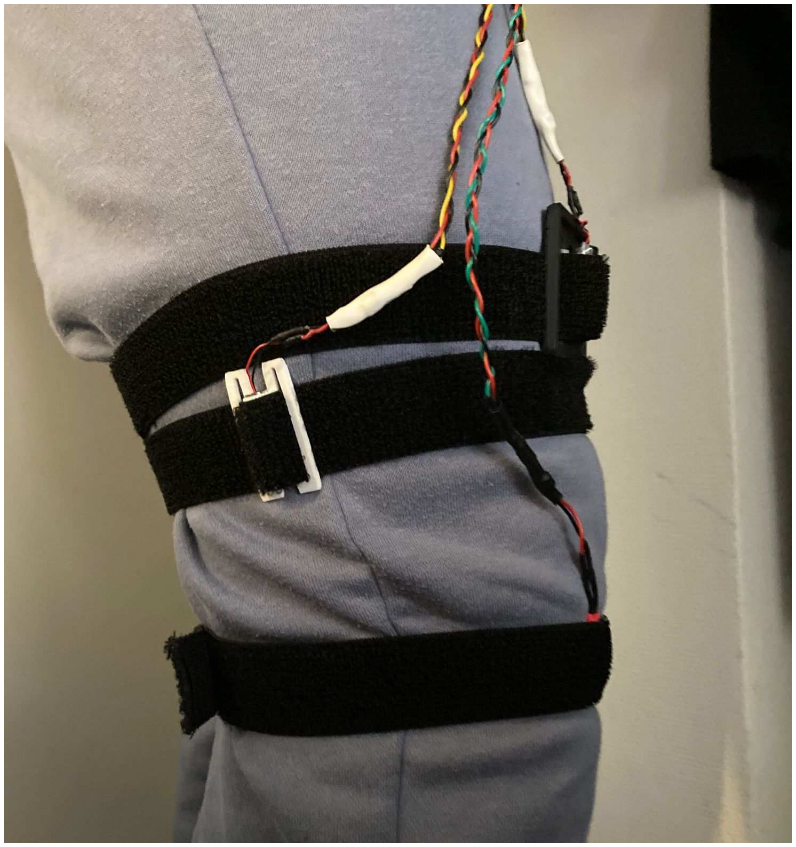

Figure 4.1: Placements of the vibration motor giving feedback on squat depth

because it was ranked as the more comfortable position out of the two ankle positions.

Figure 4.2: Placements of the vibration motor giving feedback on heel position

Chapter 5

Sensor placement

This chapter deals with answering the subquestion: 'Where can the sensors to measure correct squat technique be placed to ensure correct measurements?'. The main point of interest is the placement of the sensor to measure squat depth. The placement for the heel pressure sensor is fairly straightforward since it has to be placed under the heel. Various considerations were made in deciding where the squat depth sensor should be placed. This chapter will give insight into these considerations and a small experiment done on the placement of the squat depth sensor.

5.1 Heel pressure sensor placement

The sensor used to measure the contact of the heel with the ground is a pressure sensor constructed out of a piece of Velostat, which is an electrically conductive material. The construction of this sensor is more elaborately described in chapter 6. The function of this sensor already dictates its placement, namely under the heel of the wearer. Since this sensor is used in multiple experiments it was decided that it should be easily attachable and detachable, which led to the decision to place the sensor under the heel of the shoe of the wearer with a piece of double sided tape. This kept the sensor in place for the duration of the experiments.

5.2 Squat depth sensor placement

The sensor used to measure squat depth is an Inertial Measurement Unit (IMU) known as the MPU-6050. This sensor uses a gyroscope and accelerometer to measure its current angle. A more detailed description of the workings of this sensor and a benchmark of the sensor itself can be found in chapter 6. This sensor is positioned on the upper leg of the wearer to track the angle of this upper leg relative to the floor. Once the sensor is parallel to the ground, the upper leg should also be parallel to the ground. This means that the sensor must stay in place for the duration of a series of squats, while also being easy to attach and detach and not hinder the movements of its wearer. This leads to a few key requirements for the placement of this sensor:

- The sensor must measure squat depth correctly consistently
- The sensor must stay in place during repeated squats
- The sensor must not hinder squat performance
- The sensor must be easily attachable and detachable

To ensure that these requirements were met, the front of the upper leg on top of the clothing was chosen as the place where the squat depth sensor would be placed. This deviates from a more common placement of such a sensor, which would usually be placed on the skin and on the side of the upper leg where there is less soft tissue that moves during a squatting movement. There are various reasons why this placement was chosen over the more conventional placement. Firstly, the sensor must be easily attachable and detachable to allow for multiple participants to perform the evaluation test for the wearable in a short amount of time. To achieve this, the sensor has to be placed over the clothes and not directly on the skin, as this would inconvenience the participants too much during the experiment. Secondly, the placement of the sensor must not hinder performance during squatting and must also stay in place during the full experiment. It was observed during the test phase on vibration motor placement that the participants would often move their arms forward while descending into a squat. This movement would sometimes cause the hand to hit the sensor, nudging it out of place or startling the participant, impacting their focus on the task. To ensure that the placement of the sensor on the front of the upper leg over the clothing does not impact the measurements of the sensor itself, the experiment in the section below was conducted.

5.3 Experiment on correct squat depth sensor measurements

5.3.1 Method

To ensure that the chosen placement of the squat depth sensor (front of upper leg, over clothing) produces consistently correct measurements, an experiment was performed. In this experiment the researcher performed 3 series of 10 squats while wearing the wearable with the squat depth sensor attached. A camera is set up on a level angle to capture an image each time the sensor measures a squat

Figure 5.1: One squat from the experiment with a line drawn from the knee to the hip crease and a horizontal line

repetition to correct depth. In figure 2.7 it can be seen that the hip joint must be level with the knee joint or lower than the knee joint for a squat repetition to be to correct depth, this correlates with the upper leg being parallel to the ground or lower. The images of the experiment are then analyzed and overlaid to show how consistent the measurements from the sensor are with the chosen placement.

Figure 5.2: images from 3 series of 10 squats overlaid on one another to measure the squat depth sensor's accuracy

5.3.2 Results

In figure 5.1, a horizontal line was drawn over the top of the leg as a reference point for correct squat depth. Additionally, a line was drawn from the knee to the hip crease, to show that the squat was actually to proper depth. This is an image from one of the performed squat repetitions. The images from all of the repetitions from each series were then overlayed to create figure 5.2. In figure 5.2, images are formed from all 3 series of 10 squats performed during the experiment. Each image represent a series of 10 repetitions. As can be seen from the images, the sensor consistently measures a squat depth where the leg is parallel to the floor and to the yellow horizontal line. The images also show that the sensor stays in place during all of the repetitions. This is an important aspect to note, because a slipping sensor would lead to inaccurate measurements and this could lead to inconsistency in measurements when multiple repetitions are performed.

5.4 Conclusion

The choice to place the sensor to measure squat depth on the front of the upper leg instead of the more conventional placement on the outer part of the upper leg is one made out of practical considerations. With this placement the sensor does not obstruct the wearers movements and is easily attached and detached due to being fitted over the user's clothing. The experiment performed in this chapter shows that this placement does not hinder the ability of the sensor to accurately and consistently measure the depth of a squat. The placement of the sensor to measure heel contact with the floor was much more straightforward. This sensor was mounted to the underside of the heel of the wearer's shoe. This proved to be a sound choice as it stayed in place for long periods of time and the use of double sided tape made it easy to detach after use.

Chapter 6

Realisation

In this chapter the research questions 'How can Inertial Movement Units (IMU) be used to measure depth during a squat?' and 'How can a pressure sensor be used to measure heel contact with the ground during a squat?' will be answered. This chapter describes the design and development of the wearable.

6.1 Hardware

6.1.1 ESP32

The heart of the wearable consists of an Adafruit Feather Microcontroller with an ESP-32 onboard. This chip is outfitted with Wi-Fi and Bluetooth. The Bluetooth function of this microcontroller is used to transmit data from the wearable to a smartphone. This makes the data easily available for transfer to a computer. The sample rate for this project is 100 samples/second. This ensures that changes is the sensor measurements can be monitored precisely. This microcontroller also has a number of GPIO pins to interface with external modules such as an inertial measurement unit (MPU) and pressure sensor. The microcontroller is powered by a USB-powerbank of 20,000mAh to ensure it will keep running for the duration of the experiment.

6.1.2 MPU-6050

To measure the depth for a squat, an inertial measurement unit (IMU) is used. The specific model used is the MPU-6050. This is a relatively cheap sensor originally produced by TDK InvenSense. It features both a 3-axis gyroscope as well as a 3-axis accelerometer. The MPU-6050 is positioned on the front of the upper leg, then the value of the Y-axis is monitored to check if a squat repetitions was to sufficient depth. This is done by measuring the current angle of the MPU-6050 while it is attached to the upper leg. When the upper leg is parallel to the floor, the MPU will also be parallel to the floor, thus measuring an angle of 0°. A common problem with these IMUs is that they will experience something called sensor drift. When this occurs the values displayed by a sensor will drift over time, even when the sensor is completely still. This was solved by using a complementary filter over the data from the sensor. For the depth measurement the main sensor of the IMU that is used is the gyroscope. To counteract the drifting, a small percentage of the accelerometer readings are used to correct the gyroscope readings. This then produces a more accurate representation of the tilt angles of the IMU.

Figure 6.1: The MPU-6050 IMU in its leg strap

Benchmarking the MPU-6050 To measure if the sensor actually measures its angle correctly, an experiment was carried out using an iPhone with a level app. First, the surface was confirmed to be level using an iPhone with its level app. The accelerometer and gyroscope present in the iPhone is reliable enough to be used as a level in this case [35]. Then a triangular ruler was used to measure the accuracy of the MPU-6050 in measuring the angles needed for squat depth assessment. The MPU-6050 was the used to perform 10 movements from a known 0°to a known 90°and back, simulating a set of squats from the user test. This was done to not only measure the accuracy of the MPU, but also if any sensor drift would occur during the experiment. The results of this benchmark test can be found in figure 6.2. From the figure it can be seen that on every repetition the MPU returned to 0°. The accuracy of this measurement is crucial for the main evaluation test of the wearable. as the target depth for each squat repetition is reached when the upper leg is parallel to the ground. This occurs when the MPU-6050 measures its angle at 0°.

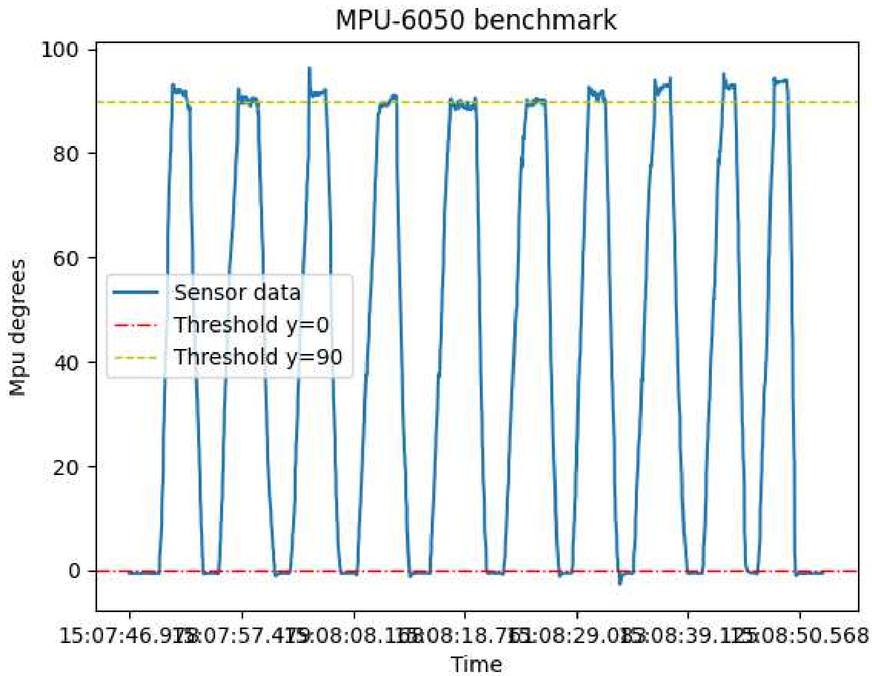

Figure 6.2: Benchmark of the MPU-6050

6.1.3 Pressure sensor

To measure the contact of the heel with the floor, a rudimentary pressure sensor was constructed using a piece of Velostat. Velostat is a packaging material developed by 3M. it is commonly used to package materials that can be harmed by electrostatic discharge because it is electrically conductive. This characteristic makes it also ideal to be used in low-cost pressure sensors. Velostat is piezoresistive, which means that its electrical resistance changes based on the amount of pressure that is applied to it.

The pressure sensor was created with this piece of velostat attached to a voltage divider. One of the uses of a voltage divider is to measure the resistance of a sensor. In this case a 10k ohm resistor was used. Because the the ESP32 development board outputs 3.3v the resistance of the pressure sensor can be calculated leading to data on the heel pressure during a squat. Because this is an analog sensor, readings are not always consistent. This is why measurements are being done on a rolling average of the sensor values. When the heel is on the ground, the resistance of the velostat is at its lowest since pressure is high. A range between 0 and 100 was chosen to represent the heel being on the ground. When a rolling average of 50 measurements passes the threshold of 100, the heel has certainly ceased to make contact with the ground.

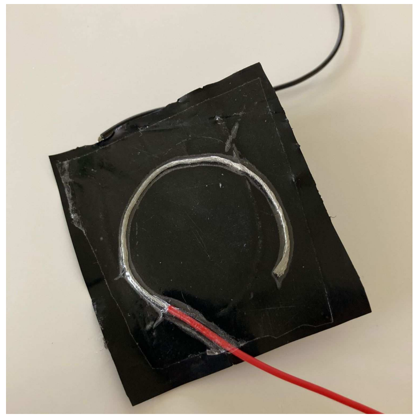

Figure 6.3: The pressure sensor made with Velostat

Benchmarking the pressure sensor For the pressure sensor it is important that the sensor does not become 'tired' after standing on it during the evaluation test. If that would be the case, the sensor would not react to heel elevation. To test this, the pressure sensor was attached to the heel of a person who then proceeded to stand on the ground for approximately 10 seconds before completely lifting their foot off the ground. This was repeated for 4 repetitions. The results can be seen in figure 6.4. The blue line represents the raw measurements straight from the sensor, while the orange line was plotted to represent the rolling average of 50 measurements that was also used to decide whether or not feedback should be provided by the wearable. As can be seen, due to the analog nature of the sensor the measurements show some variation. The rolling average however shows that every change in contact with the ground is quickly registered by the sensor, while the measurement does not surpass the threshold of 100 while the foot is in contact with the ground.

6.1.4 Vibration motors

The vibration motors that were chosen for this project are 2 cylindrical vibration motors. These motors were chosen during the experiment on actuator placement outlined in chapter 4. This was the strongest vibration motor available for this project. 2 coin shaped vibration motors were used first due to their compact size and ease of placement. The vibrations from these motors however, proved to be difficult to perceive by participants during squatting. These cylindrical vibrations motors provide a significantly stronger vibration due to an increase in rotating mass compared to the coin vibration motors. This does make them less compact and more difficult to attach to the body. The solution for this was 3D-printed casings for both motors as can be seen in figure 6.5.

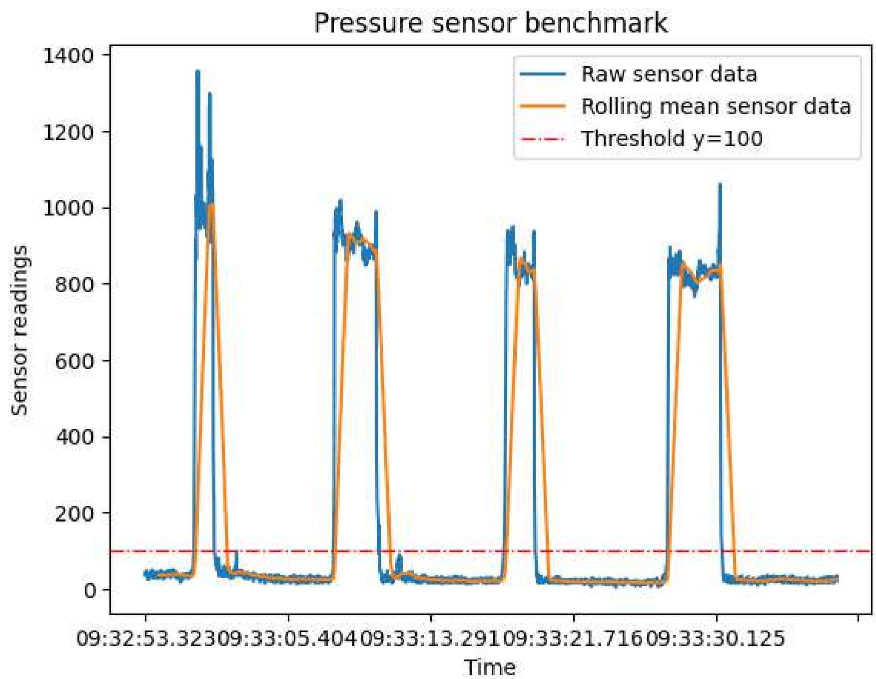

Figure 6.4: Benchmark of the pressure sensor

6.2 Wearable development

6.2.1 Prototyping

Multiple prototypes were developed and tested in an iterative process. This process consists of ideation, prototyping and test phases and was mainly focused on the way the two chosen characteristics of correct squat technique were to be measured. From the context analysis it became clear that the best way to measure squat depth was through the use of inertial measurement units (IMU). How this would be done however, was not yet explored.

During the first iteration, the idea was to take two IMUs and place them above and below the knee respectively. This way, the angle between the two IMUs can be calculated. This measurement represents the knee angle of the user of the wearable. During the prototyping phase of this iteration however, it was found that this value is not ideal for the purpose of this research. As mentioned in the section in chapter 2 on correct squat technique, optimal squat depth is defined as having the upper leg parallel to the ground at the deepest part of a squat. By calculating the knee angle of a trainee this cannot be measured reliably because the position of the upper leg realtive to the floor is not known. Also, due

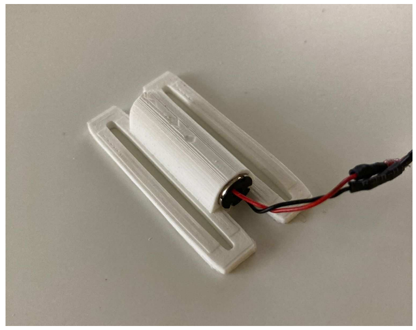

Figure 6.5: A vibration motor in its 3D-printed casing

to differences in individual limb length and proportions, a previously specified 'optimal' knee angle of for example 90°, does not ensure that all participants will have their upper leg parallel to the ground. This then concluded the first iteration.

With this in mind, in the second iteration the idea that squat depth could be measured more reliably and easily by using a single IMU and measuring its own angle during a squat repetition was born. This single IMU can then be mounted on the upper leg of the participant. This ensures that regardless of differences in limb length and proportions, squat depth is always measured by the angle of the upper leg of the participant in relation to the ground. During the prototyping phase of this project the right way to measure the angle of the IMU was further investigated. Many different libraries that interfaced with the IMU were tried, but ultimately a simple method of calculating the angle of one axis of the IMU by getting the degrees of tilt from the gyroscope of the IMU and using the readings from the accelerometer as a filter to counteract drifting of the sensor readings was used. The accuracy of this method was then tested with the benchmark of the MPU-6050 in the above section.

Measuring the second characteristic for correct squat technique was a more difficult process. In an earlier version of the wearable, knee valgus was to be the second aspect of squat technique to be measured. Knee valgus is characterized as lateral movement of the knees during a squat. The degree in which this happens is very individual and the harmfulness is as well. Multiple ways to measure this were explored before moving on to measuring heel contact with the ground.

In this first iteration, the idea was to use two of the same MPUs used to measure the squat depth, but attached on both knees to measure the lateral displacement. During the prototyping phase this idea was abandoned since this relied heavily on the accelerometer of the MPU which did not very accurately pick up the smaller movements of the knees. After tinkering with this method for a while, other options were investigated.

In the second iteration, the use of a distance sensor was proposed to measure the distance between both knees. This sensor uses ultrasonic pulses to measure distance. The sensor would be placed on one the inside of one knee and send ultrasonic pulses to the other knee. When testing the first prototype however, it was found that the knees proved to not be a suitable surface to bounce off ultrasonic signals. The angle at which the pulses hit the other knee was not completely straight so the pulses would not bounce back to the ultrasonic sensor. This sensor really only works as intended when the object to measure the distances between is positioned straight in front of the sensor.

In the last iteration to measure knee valgus, the idea to use a stretch sensor to measure when the distance between the knees changed was formed. This sensor is a conductive rubber cord that increases its resistance when pulled apart. This cord would then be attached to both knees, theoretically resulting in more resistance when the legs were further apart, and less resistance when the legs caved in. Fairly soon after the sensor arrived however, during some first measurements it was found that when stretched out, the rubber takes a long time to shrink back to its original length, making the sensor not suitable for multiple measurements in a short period of time.

After this, the idea of measuring knee valgus was abandoned in favor of measuring heel contact with the ground. This can be done by making a fairly simple pressure sensor using a piece of conductive material (Velostat) and a voltage divider. This sensor was then constructed by using a piece of Velostat and attaching a piece of wire on each side. Using a voltage divider with a 10k Ohm resistor, the amount of resistance could be measured. The results of the testing phase of this iteration can be found in the section above on benchmarking the pressure sensor.

6.2.2 Final assembly

All pieces of hardware were combined into the final prototype for the wearable. The ESP32 development board and voltage divider were stored in a fanny pack that can be worn around the waist of the participant. The MPU-6050 can be attached to the upper leg of the participant with an elastic strap with a pocket for the MPU so the participant can fit the strap comfortably on their leg before the MPU is placed inside.

The vibration motors were placed in their 3D-printed casings and attached to elastic bands with velcro for easy attachment to the upper leg and ankle areas. lastly, the Velostat pressure sensor was attached to the sole of the participants shoe by a piece of double-sided tape. Because the participants were all standing still during the majority of the experiments, this did not cause wear and tear on the sensor.

Figure 6.6: The completed wearable

Chapter 7

Evaluation

The research question 'How to evaluate the effectiveness of the wearable?' will be answered in this chapter. An evaluation test was performed with the developed wearable to determine if the wearable would work in improving squat technique of its users. The methods used and results of this test will be discussed in this chapter.

7.1 Method

7.1.1 Experiment

To evaluate the effectiveness of the wearable a user test was carried out. This user test consists of two sessions each spaced one week apart. This experiment design was chosen to test if performance increases when more time is spent using the wearable. This leads to two sets of measurements that can be analyzed in the data analysis phase of the experiment, more on this can be found in the paragraph on data analysis below.

For the evaluation test, 20 participants were split in two groups of 10 each. The first group (body location-feedback group) would receive vibrotactile feedback on the location of the body where the measurement data was also gathered, namely the upper leg area for feedback on squat depth, and the back of the ankle area for feedback on heel elevation. The second group (wrist-feedback group) would receive feedback on squat depth on the wrist of their right arm, and feedback on heel elevation on the wrist of their left arm.

In each session the participant was asked to perform 3 sets of 10 body-weight squats while wearing the vibrotactile feedback wearable. This number was chosen to maximize the amount of data collected, while keeping fatigue relatively low. During the sets, the participant would receive negative terminal vibrotactile feedback after every repetition. This means that they would only receive a feedback signal if the repetition was incorrect. After a short calibration phase to determine the starting position of the participant, they were asked to begin squatting. If a repetition was not to sufficient depth, the device would provide a feedback signal when the participant returned to their starting position. Likewise, when the participant lifted their heel off the ground during a repetition, the device would provide a feedback signal when the participant returned to their starting position.

Each session was the same, regardless of the group the participant was in or if it was their first or second session. The full test protocol can be found in appendix C, but in summary all sessions proceeded in this manner:

- Participant is asked about any limitations inhibiting their ability to partake in the experiment
- Participant reads information brochure and signs consent form
- The wearable is fitted to the participant
- Wearable is connected to smartphone
- Participant proceeds to do 3 sets of 10 squats
- Wearable is disconnected
- Participant fills out NASA TLX questionnaire

The experiments were carried out in a home setting or in a project room at the university. The portability of the wearable allowed the experiments to be carried out in many different settings which meant that not every participant had to come to the university if this was inconvenient for them. Participants were carefully selected on their lack of squatting experience. This ensures that the two groups of participants will generally perform the same at a base level.

This is a between subjects study. The outcomes of the body location-feedback group will be compared to that of the wrist-feedback group.

Data analysis During the experiment, data on squat depth and on heel pressure was recorded and sent to a smartphone. This data was then split into a .csv file with only depth measurements and a .csv file with only heel pressure measurements for each participant. Data analysis was conducted with python in a jupyter notebook. The analyses that were carried out are as follows:

- Comparing amount of correct depth measurements between groups
- Comparing amount of correct heel placements between groups
- Comparing differences in feedback adaptation between groups

Because of the small sample size of both groups ($n = 10$), a non-parametric test was used to analyze the significance of the results. For this, the Mann-Whitney U test was used. This test can be used to determine if there are significant differences between the distributions of two independent groups. The results of a Mann-Whitney U-test consist of the U-statistic and a p-value. The U-statistic has a critical value based on the population size and chosen significance level. For this study with a sample size of $n = 10$ and a chosen significance level of 0.05, the critical value is 23[36]. When the value of the U-statistic is lower or equal to the critical value, the null-hypothesis can be rejected. However, when the accompanying p-value is higher than the chosen significance level, the probability that this result was obtained by chance exceeds the chosen significance level, in this case 5%, so the results cannot be classified as statistically significant. Therefore, the null-hypothesis cannot be rejected[37].

7.1.2 NASA Task Load Index

The NASA Task Load Index (TLX) [38], was developed by Sandra Hart at the NASA Ames Research Center (ARC) in the 1980s to assess subjective workload with various human-machine interface systems. It derives an overall workload score based on ratings on six subscales:

1. Mental Demand
2. Physical Demand
3. Temporal Demand
4. Performance
5. Effort
6. Frustration

In this experiment the NASA TLX was used to obtain a subjective measurement of the workload during the squat task. The questionnaire was administered using pen and paper after the squat task had been completed. This questionnaire was chosen due to its ease in administering and relatively low mental workload.

Data analysis Each TLX questionnaire was digitized in a .csv file after completion. This resulted in a separate .csv file for the body location-feedback group and the wrist-feedback group. then, for every participant their scores on each measure were logged along with the session number. This makes the data from the NASA TLX questionnaire suitable for analysis. The scores of each respective group were then plotted next to each other to see if there was a difference between groups and between sessions. To better understand the significance of the results from the NASA TLX questionnaire, statistical tests were done. First, for every participant a total score for all measures was calculated: the sum score. This was done for both sessions. Then, just as with the objective data, an improvement score was calculated by subtracting the sum score from session 1 from the sum score of session 2. In this case, a negative improvement score signifies a lower task load in session 2, which is an improvement. Next to the improvement score, an average was taken from the sum scores of both sessions, to analyze if there was a difference in task load between the two feedback groups over both sessions. A Mann-Whitney U test was carried out to see if there are differences in the distribution of both the improvement scores of the two groups, as well as the averages of both sessions. These results can be found in the next section.

7.2 Results

The participants were asked to perform 3 sets of 10 squats while wearing the wearable, resulting in 30 squats in total. During this experiment, both their squat depth as well as the contact of their heel with the ground was measured. These were the two modalities chosen to represent a correct body-weight squat. Analysis was performed on both the depth measurements as well as the heel contact measurements. Below in figure 7.1 a graph is shown of one session with the IMU data as the blue line and the heel pressure sensor as the orange line. 2 reference lines have been drawn to show the points where correct depth was reached and where the heels lose contact with the floor. For the squat depth this is the dotted red line at $y = 0$, and for the heel data this is the dotted green line at $y = 100$.

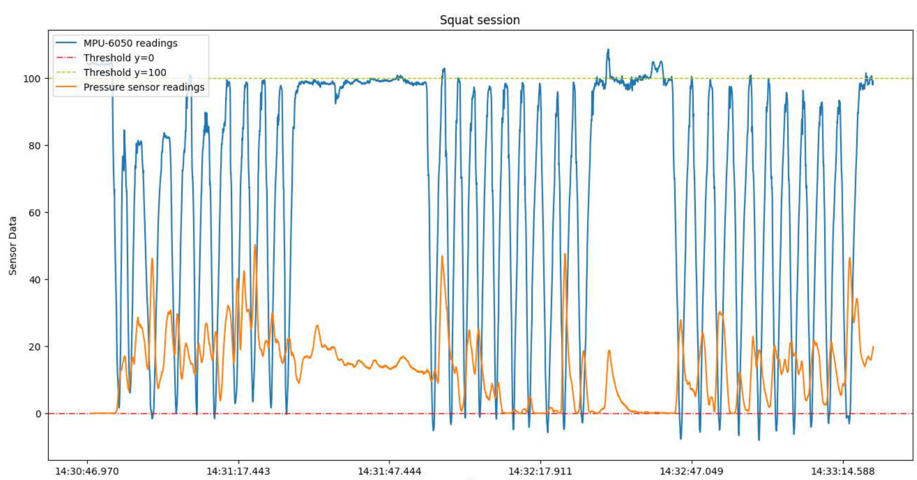

Figure 7.1: An example of the data gathered from a participant's squat session

When a participant performs a squat repetition to its full depth the negative peak of the blue line should dip below the red reference line at $y = 0$. In the example in figure 7.1 it is shown that this particular participant completed 25 repetitions to full depth and 5 repetitions that were not to full depth.

This figure also shows that the heels of this participant did not display loss of contact with the floor since the orange line never goes above the green threshold line at $y = 100$. The need for this threshold is explained in more detail in the chapter on realization of the wearable.

7.2.1 Squat depth

Performance The data from each participant was ran through a python program which calculates the peaks in the data using the `scipy.signal.find_peaks()` function. For the session in figure 7.1 this resulted in 25 correct squat depths and 30 correct heel positions. The squat depth data from both groups and both sessions was then plotted in figure 7.2 below. For the data on heel positions see the next section.

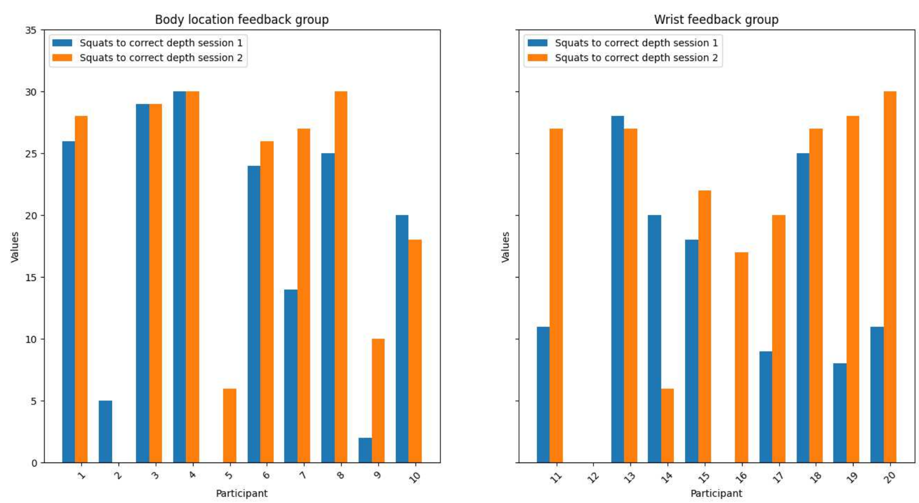

Figure 7.2: Amount of repetitions to correct depth from session 1 and 2 of the body location-feedback group vs. the wrist-feedback group

In these figures, the two bars denote the amount of squat repetitions done to depth for each participant in the first and second session respectively.

To show the difference in squat depth between groups for all participants figure 7.3 was plotted. This figure shows the amount of squats to correct depth for session 1 and session 2 between the body location-feedback group and the wrist-feedback group. As shown in the figure, The body location-feedback group exhibited a higher number of correct-depth squats in session 1 on average and continued to increase this average in session 2. While the wrist-feedback group

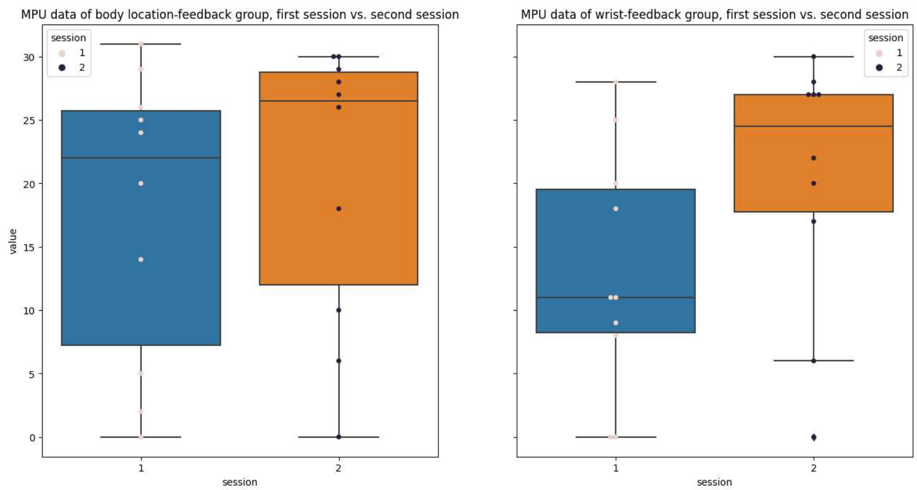

Figure 7.3: Amount of correct depth repetitions from session 1 and 2 for body location-feedback group and wrist-feedback group

started out with quite a low average of squats to correct depth in session 1, an increase can be seen in session 2. This higher average however, is still not as high as the average of session 2 from the body location-feedback group.

From the plotted figure it looks as if the body-location feedback group performs better over both session 1 and 2, but the wrist group seems to show the greatest improvement between sessions. To see if this difference is statistically significant, a Mann-Whitney U test was conducted. First, an improvement score was calculated for all participants in each group. This was done by comparing the difference between session 1 and session 2 and then storing this difference as a value. The improvement scores for both feedback groups can be found in table 7.1 and 7.2. These 2 groups of values were then used as inputs for the Mann-Whitney U test.

- ***h0***: The distributions of the two groups are the same
- ***h1***: The distributions of the two groups are different

To perform this test, `scipy.stats.mannwhitneyu()` was used to perform the Mann-Whitney U test. A significance value of 0.05 was chosen. Since $n = 10$ for both groups, the critical value for the U score is 23. The results of the test show a U-statistic of 35. This is higher than the critical value of 23, and would suggest that ***h0*** cannot be discarded. The calculated p-value in this case is 0.27, which is much higher than the significance value of 0.05. This means that ***h0*** cannot be rejected. The data shows that the two feedback groups do not show a significant difference in distribution when it comes to improved performance on squat depth between session 1 and 2.

Participant	Session 1	Session 2	Improvement
1	26	28	2
2	5	0	-5
3	29	29	0
4	30	30	0
5	0	6	6
6	24	26	2
7	14	27	13
8	25	30	5
9	2	10	8
10	20	18	-2

Table 7.1: Amount of correct depth squats and improvement score for the body location-feedback group

Participant	Session 1	Session 2	Improvement
11	11	27	16
12	0	0	0
13	28	27	-1
14	20	6	-14
15	18	22	4
16	0	17	17
17	9	20	11
18	25	27	2
19	8	28	20
20	11	30	19

Table 7.2: Amount of correct depth squats and improvement score for the wrist-feedback group

Feedback adaptation To gain more insight into how both groups reacted to feedback given on incorrect technique, an analysis was done on the adaptation to feedback. To do this, each participant was given a score on how well they adapted their performance after they had received feedback. This score was calculated by looking at how many repetitions it took for a participant to correct their technique after feedback was given. Every repetition was given a value of either 0 or 1, based on whether feedback was given and technique was improved, or feedback was given but ignored respectively. This leads to 4 possible scenarios for every repetition:

- The current repetition is the first one in the session: A value of 0 is given
- The current repetition is being done correctly: A value of 0 is given
- Feedback is provided to the current repetition but the previous repetition was done correctly: A value of 0 is given
- Feedback is provided to the current repetition and the previous repetition also had feedback provided: A value of 1 is given

For the squat session in figure 7.1, This leads to a total score of 3. On the first repetition feedback was given, but since this was the first repetition it gets a score of 0. On the second repetition feedback is also given, and since feedback was also given on the previous repetition this one gets a score of 1. The following repetition is done to correct depth which means the feedback was properly applied. Therefore, this repetition gets a score of 0. This is then done for every repetition in the session, which leads to an overall score of 3 for this session.

The scores from both sessions from each participant were then combined, leading to one set of scores for both the body location-feedback group and the wrist-feedback group. A Mann-Whitney U test was then performed on this data.

- ***h0***: The distributions of the two groups are the same
- ***h1***: The distributions of the two groups are different

The results of the Mann-Whitney U test showed a U-statistic of 37.5 and a p-value of 0.36. This means that the U statistic is above the critical value of 23, so the null-hypothesis cannot be rejected. The fact that the p-value is above the chosen level of significance of 0.05 signifies even more that there is no significant difference between the distribution of the body location-feedback group and the wrist-feedback group.

7.2.2 Heel elevation

Performance To calculate the amount of times the heels of a participant remained in contact with the floor, a similar method was used to calculate the peaks in this data as was the case with the squat depth data. once again, the `scipy.signal.find_peaks()` function was used to identify peaks above a value of $y = 100$. A peak value above this threshold means that a participant's heel did not make contact with the floor at that point. Figure 7.4 Shows the amount of correct heel positions of each participant from both sessions 1 and 2, separated by feedback group.

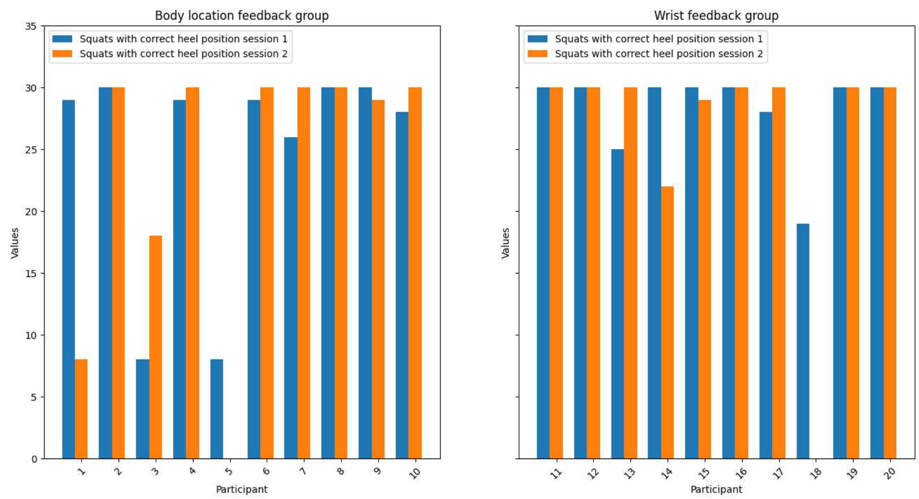

Figure 7.4: Amount of correct heel position repetitions from session 1 and 2 for body location-feedback group and wrist-feedback group

To better show the difference between groups, Figure 7.5 was plotted. This figure shows that both groups kept their heels on the ground quite well throughout both sessions. However, this figure also shows that in session 2 the body location-feedback group seems to contain a few participants that had trouble with keeping their heel in contact with the floor. Still, the mean of this group is quite high over both sessions.

To see if there was a significant difference in improvement between the body location-feedback group and the wrist-feedback group when it comes to heel elevation during a squat, again a Mann-Whitney U test was carried out. $n = 10$ for both groups here which results in a critical U statistic of 23. The chosen level of significance was 0.05. The results of the Mann-Whitney U test show a U statistic value of 58.5, which is much higher than the critical value. The calculated p-value is 0.54, which means that ***h0*** can also not be rejected here. This means that based on this data the two groups show a similar distribution, and one group did not improve significantly more than the other.

Feedback adaptation In a similar fashion to measuring the feedback adaptation in squatting to depth, this was also measured for the heel elevation. Each repetition from every participant was given a score based on their reaction to

Participant	Session 1	Session 2	Improvement
1	29	8	-21
2	30	30	0
3	8	18	10
4	29	30	1
5	8	0	-8
6	29	30	1
7	26	30	4
8	30	30	0
9	30	29	-1
10	28	30	2

Table 7.3: Amount of squats with correct heel position and improvement score for the body location-feedback group

Participant	Session 1	Session 2	Improvement
11	30	30	0
12	30	30	0
13	25	30	5
14	30	22	-8
15	30	29	-1
16	30	30	0
17	28	30	2
18	19	0	-19
19	30	30	0
20	30	30	0

Table 7.4: Amount of squats with correct heel position and improvement score for the wrist-feedback group

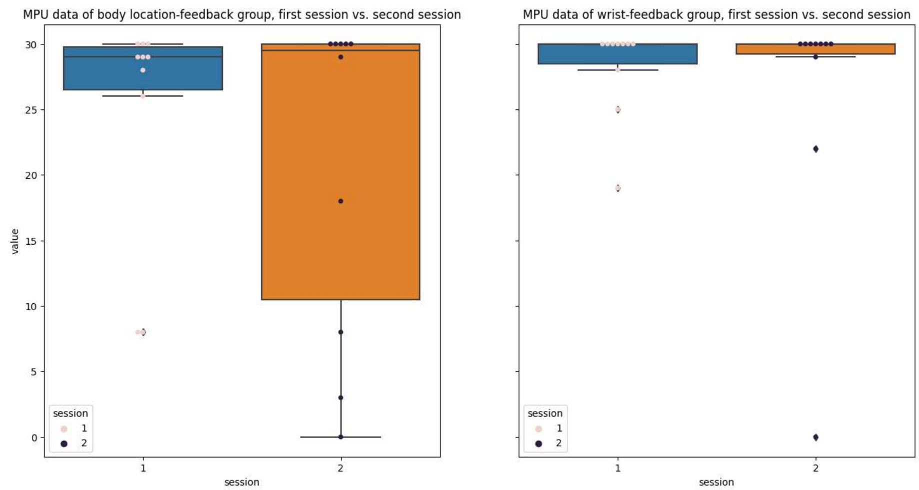

Figure 7.5: Amount of correct heel position repetitions from session 1 and 2 for body location-feedback group and wrist-feedback group

feedback provided. Scores from both sessions were then combined per participant, resulting in one score per participant and a list of scores for both the body location-feedback group and the wrist-feedback group. Then, a Mann-Whitney U test was performed on this data.

- ***h0***: The distributions of the two groups are the same
- ***h1***: The distributions of the two groups are different

The results of the Mann-Whitney U test were a U-statistic of 60 and a p-value of 0.37. This means that the null-hypothesis cannot be rejected since the U-statistic is higher than the critical value of 23 and the p-value is higher than the chosen level of significance of 0.05.

7.2.3 Nasa TLX

The results of the NASA TLX questionnaire as pictured in figure 7.6, show some differences between the two feedback groups. On the left the body location-feedback group is pictured, and on the right the wrist-feedback group. In this figure both sessions of a group are plotted in the same graph, so each graph has two data-points belonging to the same participant. Differences between the two groups can mostly be seen in the performance, effort, and frustration scores. It seems that over two sessions the body location-feedback group perceives their performance to be higher, while their effort and frustration are lower than that of the wrist-feedback group.

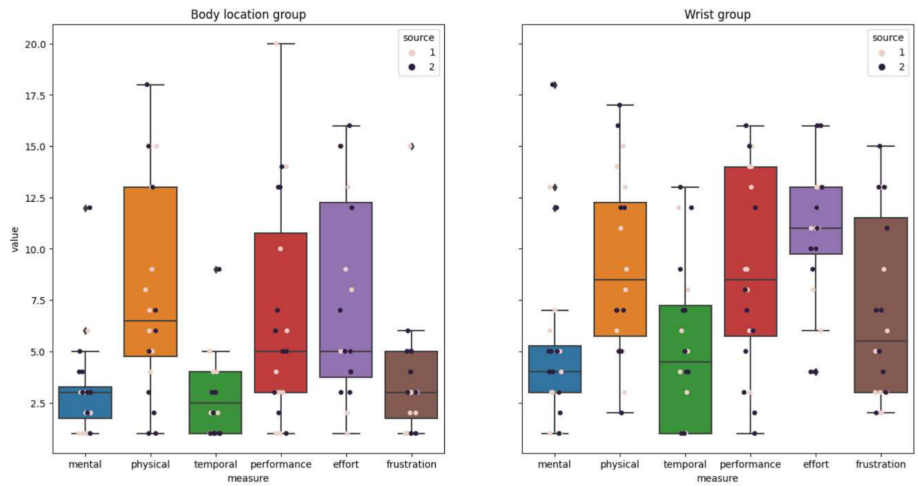

Figure 7.6: TLX answers for both sessions divided by feedback group

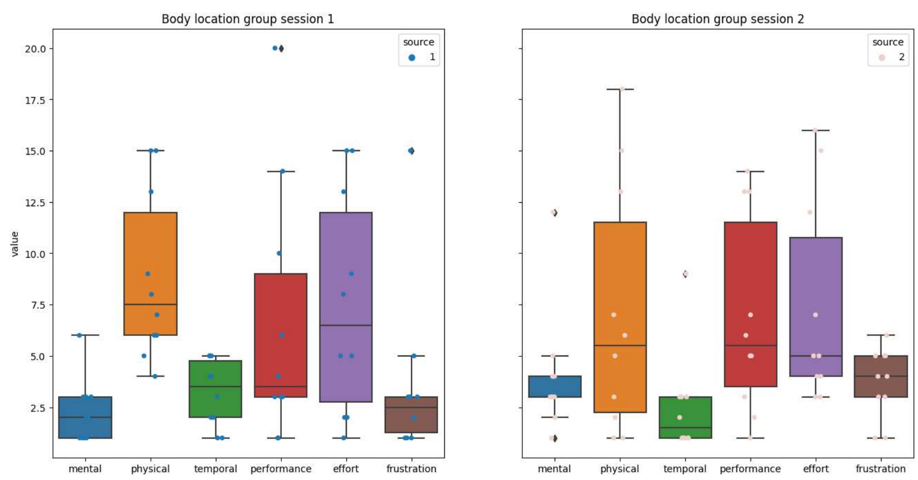

Figure 7.7: TLX answers for the body location-feedback group, session 1 vs. session 2

Body location-feedback group In figure 7.7 the answers for the TLX questionnaire from the body location-feedback group are plotted. Pictured left is session 1, and right is session 2. The values of all measures in both sessions seem to be in the lower part of the scale, which is positive. The perceived performance however seems to be rated worse in session 2 than in session 1, even though results from the squat depth data, and in most cases also the heel pressure data, show an improvement in session 2 over session 1.

Participant	Session 1	Session 2	Improvement	Session 1&2 average
1	24	25	1	24,5
2	47	46	-1	46,5
3	18	25	7	21,5
4	16	20	4	18
5	73	72	-1	72,5
6	41	38	-3	39,5
7	13	11	-2	12
8	12	20	8	16
9	43	34	-9	38,5
10	32	25	-7	28,5

Table 7.5: Sum scores for NASA TLX answers of body location-feedback group (lower is better)

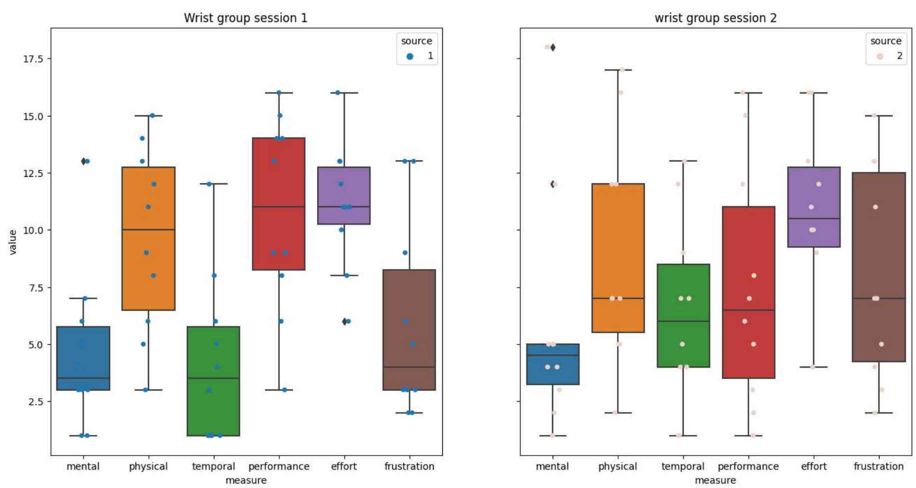

Figure 7.8: TLX answers for the wrist-feedback group, session 1 vs. session 2

Wrist-feedback group As shown in figure 7.6, the TLX answers from the wrist-feedback group show an overall higher score on all six measures compared to the body location-feedback group. In figure 7.8 the values of both sessions from the wrist group are plotted. Perceived performance is the only measure that seems to significantly improve from session 1 to session 2. This corresponds to what can be seen in the data from the squat depth sensor in figure 7.3. The other measures, apart from physical demand, all seem to be scored relatively similar in session 1 and 2, or a little worse in session 2.

Statistical analysis To test if there are significant differences between the NASA TLX answers of both feedback groups, two Mann-Whitney U tests were

Participant	Session 1	Session 2	Improvement	Session 1&2 average
11	52	40	-12	46
12	51	67	16	59
13	57	42	-15	49,5
14	44	35	-9	39,5
15	65	63	-2	64
16	42	70	28	56
17	56	75	19	65,5
18	16	13	-3	14,5
19	44	42	-2	43
20	34	24	-10	29

Table 7.6: Sum scores for NASA TLX answers of wrist-feedback group (lower is better)

carried out. since the sample size for both groups again is $n = 10$, the critical value of the U statistic is 23, the chosen significance level is 0,05. In table 7.5, and table 7.6, the sum scores, improvement scores and averages over both sessions can be seen for the body location-feedback group and wrist-feedback group respectively. The first test, comparing the improvement scores of both groups, yielded a U statistic of 60 with a p-value of 0,47. The U statistic of this test is above the critical value of 23, and the high p-value suggests that there is not a significant difference between the distribution of the two groups. The second test compared the average sum score of both sessions between the two feedback groups. This test resulted in a U statistic of 24,5 with a p-value of 0,058. This means that differences between the averages over two sessions of the two feedback groups is not statistically significant.

7.3 Conclusion

There seems to be no statistical significant difference in performance between the group that received feedback on the more natural body location and the group that received feedback on the wrists. Deceivingly, in some of the plots it looks as if the group that received haptic feedback on the same place on the body where the measurement was taken (body location-feedback group) performed better on squatting to sufficient depth than the group that received their haptic feedback on their wrist (wrist-feedback group). Similarly, when a Mann-Whitney U test was carried out to look for significant changes in improvement between these two groups in keeping their heels in contact with the ground, it was found that the groups do not significantly differ from each other in this characteristic as well.

The effect of the haptic feedback in improving technique also shows no difference between the two feedback locations. Both groups seem to not respond significantly different to feedback given on incorrect technique.

Comparing the sum scores from the NASA TLX questionnaire of both groups with a statistical test showed no significant difference in perceived task load between the body location-feedback group and the wrist-feedback group. Ratings on individual dimensions such as effort and frustration may differ, but this difference cannot be called significant since these dimensions are a small part of a larger validated questionnaire that is meant to be evaluated on a combination of all its dimensions.

Chapter 8

Dicussion

8.1 Evaluation of the wearable

This study aimed to investigate the difference in actuator placement on a haptic feedback wearable for improving squat performance. Two different feedback locations were tested: the wrists, and a more natural location on the body for each modality that was measured. The data gathered during this study indicated that squat performance did not differ significantly between the two feedback locations. This seems to coincide with findings by Stepp and Matsuoka in a 2011 study [18] referenced in chapter 2. In this study four different actuator placements were tested during a simple task involving moving the index finger. It looks as if the findings from that study also transfer over to a more complex motor task involving the full body such as a squat. Just like the experiment carried out in this report, the study by Jan van Erp[20] also found no differences in performance between localized haptic feedback and a more generic form of visual feedback during an experiment on rowing.

When looking at the various plots in chapter 7, it seems as if the body location-feedback group starts out stronger than the wrist-feedback group when it comes to squatting to proper depth. However, after a statistical analysis this difference does not appear to be significant.

8.2 Implications

The results from this research show that in this specific situation location of feedback does not make a difference in motor task performance. This seems to contradict the findings of Mikula et al. [19], who argued that a specific spatial integration between touch and proprioception exists, where a more natural feedback position improved the position sense of the participants. This piece of research focused on the index finger, so for the more natural placement of the haptic actuators the tip of the index finger was chosen. It can be argued that the tip of the fingers is one of the most sensitive spots on the human body, so more receptive to vibrotactile feedback signals. Their other feedback location was the shoulder of the participants, which is arguably a place on the body where touch signals are more crudely interpreted than on the tip of the finger. It could therefore be possible that the difference in performance was not necessarily a result of the relation between the position of the feedback and the performed movement, but of a more sensitive spot on the body versus a less sensitive one. This could also have been the case with the research carried out in this report. Perhaps the wrists are a more suitable location for vibrotactile feedback signals than the upper leg and ankle. This could then negate the effects that a more natural feedback location may possibly have had on the squat performance of the participants. Participants that may already wear a smartwatch in daily life could be more used to receiving feedback on the wrists and have an advantage in this case.

The research carried out in this report adds to the body of work on haptic feedback wearables being used in a sports context. Specifically on how placement of haptic actuators influences performance in a motor task. Where the study by van Erp [20] used haptic feedback for the localized movement-specific feedback scenario and a visual display for the generic feedback scenario, the experiment described in this report used vibrotactile feedback for both the localized and generic scenarios. Given the fact that in both studies there was no significant difference in performance between the two feedback groups, this could suggest that one modality of feedback does not have clear advantages over another feedback modality. So visual feedback could be just as effective as haptic feedback, or auditory feedback. As Sigrist et al. [12] hypothesize in their review on augmented feedback in motor learning, a multimodal feedback strategy could perhaps even be more effective in driving motor learning than unimodal feedback.

In this experiment, two aspects of squat technique were chosen for providing vibrotactile feedback. These characteristics could be interesting for someone involved in competitive strength sports such as powerlifting. Squatting to sufficient depth is mandatory here, and this wearable could help these athletes in training to ensure that they always squat to appropriate depth. Keeping the heels on the ground during the entire repetition is also necessary to produce the maximum amount of force. This is needed to lift the most amount of weight possible. For a more general audience that wants to get into strength training, this wearable could also be useful, but this population will first need proper coaching to help them understand correct squatting technique and perform a correct squat. Then they could use this wearable periodically to check if their technique is still up to par or not. The competitive strength athlete would be able to use this device more autonomously, as they already know how to perform the exercise, and can use this device to get feedback on key performance indicators for their specific sport.

Will devices like this replace personal trainers altogether in the near future? Probably not. They can however provide a trainee with objective data about their performance without the need for a third party to give them feedback on their technique. This means that devices like this could also be used as a tool for personal trainers or fitness instructors to more effectively teach certain movement patterns without them needing to personally give feedback to their clients about their technique all the time. This can make their job more efficient as they can potentially save a lot of time on correcting technique and can instead spend more time on the initial teaching of correct technique. This can in turn make coaching or personal training available for more groups of people, as they would probably need less sessions where the trainer is present to perform the movement correctly. One caveat of this is that personal training can become less personal when too much focus is placed on technology to do the job of the trainer. It should perform more as an extension of the trainer rather than a replacement.

8.3 Limitations

The research carried out in this project focuses on the differences between different placements of haptic actuators and the influence this has on motor task performance. These experiments focus on acquisition performance of the participants, not motor learning. To assess motor learning performance, the experiment should have consisted of more sessions, with at least a retention test to to assess performance without wearing the haptic feedback wearable.

As mentioned in the previous section, the placements of the haptic motors were not chosen on their level of perceptiveness to haptic feedback. This could have led to skewed performance, as the wrist-feedback group may have been more used to receiving vibrotactile feedback on that location, whereas for the body location-feedback group this was likely not the case.

The small sample size of this study ($n = 20$) makes it difficult to generalize the results of the experiments. This sample size restricts the statistical power of the analysis and limits the ability to detect subtle differences between the two feedback groups. This can also exacerbate the effects of external factors such as varying degrees of mobility and varying limb lengths in participants, influencing their ability to squat to depth without raising their heels off the ground.

The current statistical methods used in this report do not account for fine grained analysis of which factors in the research population contributed to difference in performance like for example a logistic regression model could.

Finally, There was no control group in this study that did the experiments without receiving haptic feedback during the trials. This makes it difficult to make claims about the effects haptic feedback has on squat performance in general.

8.4 Recommendations

Based on the results of the evaluation test of this haptic feedback wearable a few recommendations can be made for future research.

This research focused on the measuring of two modalities in a squat: heel elevation off of the ground, and squat depth. It seems that for these modalities it does not make much of a difference where haptic actuators are placed to give feedback on technique. However, this might not be the case when more modalities are measured or when a more difficult motor task is being evaluated. It could be that the squat as a motor task does not have a high enough cognitive demand to see any meaningful differences in performance with different feedback locations. Therefore, further research could explore if feedback location plays a bigger role in improving performance when feedback has to be given on more modalities or on more complex motor tasks.

In this research, one simple buzz was used to provide haptic feedback to the user of the wearable. Another avenue for research could be to gain insight on different feedback patterns and their placement on the body. Some feedback patterns may be interpreted differently on different body locations.

More placements for haptic motors can be investigated to see if other placements might be more natural than the ones described in this report.

To assess the differences in motor learning performance of actuator placement for haptic feedback, further testing can be done with a larger research population and a longer experiment duration. With a control group of participant that are not subjected to haptic feedback during experiment trials, the effects of haptic feedback in a more general sense can be explored. Also, when enhancing the experiment with more sessions and a retention test without the wearable after the experiment, more insights can be gained on motor learning effects of a haptic feedback wearable.

In this experiment the research population was fairly homogeneous, with all of the participants being in the same age range (20-30), and all having no prior squatting experience. An experiment with different age groups or different experience levels might yield different results.

Chapter 9

Conclusion

In this chapter the main research question of this project will be answered, after answering the five sub-questions.

RQ: What is the effect of two different actuator placements (natural/non natural) from a haptic feedback wearable on performance of a series of squats

SQ1: How can Inertial Measurement Units (IMU) be used to measure depth during a squat?

SQ2: How can a pressure sensor be used to measure heel contact with the ground during a squat?

SQ3: Where can the sensors to measure correct squat technique be placed to ensure correct measurements?

SQ4: Where can the vibrotactile actuators be placed in the localized feedback scenario to provide comfortable, effective and intuitive feedback?

SQ5: How to evaluate the effectiveness of the wearable?

9.1 SQ1: How can Inertial Measurement Units (IMU) be used to measure depth during a squat?

As shown in chapter 6, a cheap IMU such as the MPU-6050 used in this project can measure squat depth in a relatively straightforward way. Mounted on the front of the upper leg, it registers its tilt angle relative to a flat position(0 degrees tilt on all axes). When the wearer descends into a squat and thus bends the leg on which the IMU is attached, the tilt angle of the IMU will move closer to its flat position. When the tilt angle of the Y-axis of the IMU reaches zero, this means that the upper leg of the wearer is perpendicular to the ground. This in turn means that the current squat repetition was done to sufficient depth (see chapter 2 section 1).

9.2 SQ2: How can a pressure sensor be used to measure heel contact with the ground during a squat?

In chapter 6 the construction of a pressure sensor is discussed. This sensor can be easily constructed by using a piece of piezoresistive material (Velostat) and a voltage divider. This sensor is then attached to the heel of the user. When the heel of the user makes contact with the ground, pressure is applied to the sensor. When more pressure is applied, the electrical resistance of the piece of Velostat is reduced. This means that the amount of pressure on the pressure sensor indicates whether the heel of the user is in contact with the ground or not.

9.3 SQ3: Where can the sensors to measure correct squat technique be placed to ensure correct measurements?

As discussed in chapter 5, the IMU sensor is positioned on the front of the upper leg, over the clothing of the wearer. This means that the tilt angle of the Y-axis of the sensor can be used to measure squat depth. This placement ensures consistently correct measurements, while not hindering the performance of the wearer by interfering in the squat movement. Placing the sensor over the clothing of the wearer does not impact measurement accuracy and aids in easily attaching and detaching the sensor before and after usage. The pressure sensor is attached under the heel of the wearer, since this is the part of the foot that is being tracked. In the current prototype this sensor is secured with a piece of tape to the underside of the wearer's footwear. This keeps the sensor in place and ensures consistent measurements during the experiment.

9.4 SQ4: Where can the vibrotactile actuators be placed in the localized feedback scenario to provide comfortable, effective and intuitive feedback?

In chapter 4, the placement of the vibration motors for the body location-feedback group is discussed. A group of four participants was asked to rate different placements for both of the squat performance metrics on comfort, vibration strength and intuitiveness in the context of the squat mechanic being measured. From the experiment conducted in this chapter it was concluded that the best place to attach the motor to provide feedback on squat depth was the front of the upper leg, right under the location of the sensor. This position was unanimously chosen by all participants as the most comfortable position to receive a vibrotactile feedback response while also being the most intuitive. For the motor giving feedback on heel position, the back of the ankle was chosen as the most optimal location to provide feedback. This was also rated as the most comfortable position to receive a vibrotactile signal, while the ratings for vibration strength were also the highest and intuitiveness scores where similar with the side of the ankle.

9.5 SQ5: How to evaluate the effectiveness of the wearable?

The effectiveness of the wearable in improving squat performance was tested during an evaluation test in chapter 7. This experiment consisted of two groups of participants each performing two sessions of squats spaced one week apart. The participants were put in either the body-location feedback group which received vibrotactile feedback on their squat technique roughly on the places on their body where the technique measurements were taken, or the wrist-feedback group, which received vibrotactile feedback on their squat technique on both wrists. Each session consisted of the participant performing 3 sets of 10 squats, receiving negative vibrotactile feedback after every repetition. Which means that they only received feedback on the parameters that were performed incorrectly. At the end of each session participants were also asked to fill out a questionnaire (NASA TLX) to rank their workload. The data from these experiments was then used to analyze if there was a difference in performance between the two groups with a Mann-Whitney U test. This is a non-parametric test to investigate if there are significant differences between the distributions of two groups.

9.6 RQ: What is the effect of localized versus generic feedback from a vibrotactile feedback wearable on performance of a series of squats?

During this project a wearable has been developed that uses haptic vibrotactile feedback to help users improve their squat technique. First, a context analysis was done to get information on what the state-of-the art is for haptic feedback in sports and for motor learning, and if there are already comparable projects and products out there, and on what constitutes good squat technique.

An evaluation test was done to see if the placement of the vibrotactile actuators has any influence on the improvement in performance over two sessions of squats. From the data gathered on the two groups, no significant difference can be observed between feedback on the body location and feedback on the wrists. The plots for the NASA TLX scores do show a minor difference in some metrics. The body location-feedback group reported a lower average effort while performing the squats, while their frustration levels were also lower than those of the wrist-feedback group. However, the results of statistical analysis do not show a significant difference between the total perceived task load for both groups.

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Appendix A

Brochure and consent form for pre-tests

UNIVERSITY OF TWENTE.

Enschede, date ……….

Dear reader,

In this letter, we would like to inform you about the research you have applied to participate in. The experiment will take place on ………., in room …….. of the ……. building or at (address). This experiment will be part of exploratory research for the proposed project, entitled “Designing a haptic feedback wearable for motor learning”, where we will try to design and develop a haptic feedback wearable for motor learning in a squat. The results of this experiment can also be used in further research towards using haptic wearables.

During the experiment you will be asked to perform a series of bodyweight squats while wearing a prototype of a haptic feedback wearable. It is important that you do not have any pre-existing injuries preventing you from performing this exercise. After this you will be interviewed about your experience, the different feedback patterns and the different locations used during the experiment. Results from this experiment will be used as a basis to determine what kind of feedback needs to be given where on the body to develop a wearable that gives a user useful information about squat form and how to correct it for the purpose of motor learning.

You can still decide at the end of the experiment and any time after the end of the experiment, that your data may not be included in the research after all. Other relevant aspects are that your data will be handled in a confidential manner, no personal identifiable data will be collected and that the data will never be disclosed to third parties without your permission in the consent from.

The experiment lasts for a maximum of 45 minutes. After the experiment there is space to ask questions and leave your email address with the researcher if you want to be updated with the results after this research is finished.

If you have any questions not addressed by this brochure, please do not hesitate to ask. If you want to talk about this study with an independent person, contact the Ethics Committee of EEMCS at ethicscommittee-cis@utwente.nl

Coos Pot

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Group	PP nr.

Consent form

UNIVERSITY OF TWENTE.

The University of Twente and the Department of EEMCS support the practice of protecting research participants' rights. Accordingly, this project was reviewed and approved by an Institutional Ethical Board. The information in this consent form is provided so that you can decide whether you wish to participate in our study. It is important that you understand that your participation is considered voluntary. This means that even if you agree to participate you are free to withdraw from the experiment at any time, without penalty.

The aim of this experiment is to collect information on the perception of vibrotactile feedback patterns using a haptic feedback wearable. You will be asked to wear the wearable device while performing a series of bodyweight squats. During these squats you will receive vibrotactile feedback. The results of this experiment will be used in a project for a master's thesis focusing on developing a haptic feedback wearable for motor learning.

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This experiment is part of research for a master's thesis done at the Human Media Interaction group at the University of Twente. The experiment will take place in person at a location of your preference and/or convenience. Only anonymous responses to interview questions will be collected.

Non-identifiable data can be made available to other researchers in an anonymized dataset. This experiment poses no known risks to your health. If you have any questions not addressed by this consent form, please do not hesitate to ask. If you want to talk about this study with an independent person, contact the Ethics Committee of EWI at ethicscommittee-cis@utwente.nl.

Declaration of consent (please tick each checkbox if you consent)

◯ **1.** I agree to participate in this study

◯ **2**. I have read the instructions above and understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

◯ **3.** I agree for my non-identifiable data to be made available to other researchers in an anonymized dataset.

_______________________________________ ___________________

Name and signature participant Date

_______________________________________ ___________________

Name and signature researcher Date

Appendix B

Brochure and consent form for evaluation test

UNIVERSITY OF TWENTE.

Enschede, date ……….

Dear reader,

In this letter, we would like to inform you about the research you have applied to participate in. The experiment will take place on ………. and ……… , in room …….. of the ……. building or at (address). This experiment will be part of research for the proposed project, entitled “Designing a haptic feedback wearable for motor learning”, where we will try to design and develop a haptic feedback wearable for motor learning in a squat. The results of this experiment can also be used in further research towards using haptic wearables.

This experiment consists of two sessions in which you will be asked to perform a series of bodyweight squats while wearing a haptic feedback wearable. It is important that you do not have any pre-existing injuries preventing you from performing this exercise. After this you will be asked to fill in a questionnaire about your experience.

Results from this experiment will be used to explore how haptic feedback can be used to develop a wearable that gives a user useful information about squat form and how to correct it for the purpose of motor learning.

You can still decide at the end of the experiment and up to one day after the end of the last experiment, that your data may not be included in the research after all. After this, the data will be anonymized and can therefore not be linked back to a person anymore. This completely anonymized data may be stored for up to 5 years. Other relevant aspects are that your data will be handled in a confidential manner, no personal identifiable data will be stored and that the data will never be disclosed to third parties without your permission in the consent from.

Each session lasts for a maximum of 25 minutes. After the experiment there is space to ask questions and leave your email address with the researcher if you want to be updated with the results after this research is finished.

If you have any questions not addressed by this brochure, please do not hesitate to ask. If you want to talk about this study with an independent person, contact the Ethics Committee of EEMCS at ethicscommittee-cis@utwente.nl

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Faculty of EEMCS
University of Twente

Group	PP nr.

Consent form

UNIVERSITY OF TWENTE.

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The University of Twente and the Department of EEMCS support the practice of protecting research participants' rights. Accordingly, this project was reviewed and approved by an Institutional Ethical Board. The information in this consent form is provided so that you can decide whether you wish to participate in our study. It is important that you understand that your participation is considered voluntary. This means that even if you agree to participate you are free to withdraw from the experiment at any time, without penalty.

The aim of this experiment is to collect data from a haptic feedback wearable designed to aid in motor learning for squats. You will be asked to wear the wearable device while performing a series of squats with no additional weight added. During these squats you will receive vibrotactile feedback. After performing the series of squats you will be asked to fill in a questionnaire about your experience. The results of this experiment will be used in a project for a master's thesis focusing on developing a haptic feedback wearable for motor learning.

This experiment is part of research for a master's thesis done at the Human Media Interaction group at the University of Twente. The experiment will take place in person at a location of your preference and/or convenience. The data that will be collected consists of anonymized sensor readings (gyroscope, accelerometer and pressure sensor) and anonymized questionnaire answers.

Non-identifiable data can be made available to other researchers in an anonymized dataset if you tick the third button below. This experiment poses no known risks to your health. If you have any questions not addressed by this consent form, please do not hesitate to ask. If you want to talk about this study with an independent person, contact the Ethics Committee of EWI at ethicscommittee-cis@utwente.nl.

Declaration of consent (please tick each checkbox if you consent)

- ◯ **1.** I agree to participate in this study
- ◯ **2**. I have read the instructions above and understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.
- ◯ **3.** I agree for my non-identifiable data to be made available to other researchers in an anonymized dataset.

______________________________ ________________

Name and signature participant Date

______________________________ ________________

Name and signature researcher Date

Appendix C

Testplan evaluation test

Experiment design

Introduction
This experiment consists of 2 session spaced one week apart. In each session the participant will be asked to perform the same series of squats while wearing a haptic feedback wearable. The participants are split up into two groups. One group will receive feedback on the location on the body where the technique measurements are also taken, the other group will receive feedback on both wrists. The two session design was chosen to observe if there is a learning effect between sessions one and two, and if the location of feedback influences this learning effect.

Modalities measured
Squat depth: After each repetition vibrotactile feedback will be given if the squat was not to depth. Correct depth is at least 90 degrees. Depth will be measured by one IMU placed on the upper leg of the participant

Heel elevation: after each repetition feedback will be given when the heel came off the ground during the repetition. A correct repetition will have no heel elevation. Heel elevation will be measured by a pressure sensor under the heel of the participant

Groups (group size 10)
Group 1: haptic actuators will be placed on locations on body where measurements will also be gathered (knee/upper leg, heel/ankle)

Group 2: Haptic actuators will be placed on both wrists like in a smartwatch. Right wrist for one modality and left wrist for the other.

Incorrect technique/correct technique
A repetition will be deemed correct when no vibrotactile feedback has been given on both of the 2 modalities. This means a squat depth of at least 90 degrees and heels that have been on the ground for the entire repetition.

Variables
Independent variable/Factor: place of feedback
Dependent variable: amount of correct squats

External variables:
- Variation in squat ability -> Only inexperienced people
- Variation in mobility -> Stretching before squats

Hypotheses
H0: Location of feedback has no effect on squat performance
H1: Feedback on the location of the measurements leads to increased squat performance compared to feedback on the wrists

Schedule (~15 minutes)

1. Participant enters
2. Brief participant on experiment
3. Correct squat technique explanation
4. Stretching/mobility exercises
5. Fitment of wearable
6. Calibration of wearable
7. 10 squats
8. 1 minute rest
9. 10 squats
10. 1 minute rest
11. 10 squats
12. Removal of wearable
13. Questionnaire
14. Further questions

Appendix D

NASA TLX questionnaire

Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High