MASTER THESIS

Concurrent Haptic Feedback for Improving the Body Balance of Front and Back Crawl Swimming

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15-01-2023

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ABSTRACT

In this thesis the development and testing of a wearable swimming device, that gives concurrent tactile feedback on body balance, will be discussed and evaluated. **Purpose:** Feedback systems for teaching swimming are usually limited by a coach or a device giving terminal feedback, since during swimming senses are partially obscured and there is no room for additional movements to be able to receive concurrent feedback. A haptic display can be used to provide a swimmer with concurrent feedback and aid with the learning of the correct swim technique. One key variable that can be very indicative of a swimmers' performance is the body balance; the ability to maintain a correct angle of the body around the bilateral axis. This study sets out to develop a wearable system to explore what influence haptic feedback on the body angle has on the overall body balance of swimmers. **Methodology:** A wearable device was developed that is worn, with a harness, on the back, and makes use of an IMU to measure the body angle. A suitable location for administering haptic vibrations is found by testing the perceivability of several locations by the researcher himself and thereafter test and verify these locations and a suitable metaphor with three participants. When the haptic display functions are verified, a larger group of 18 participants has been asked to swim with the wearable, firstly without any feedback (baseline phase), secondly with feedback (feedback phase), and finally without feedback again (retention phase). After every swimming bout the participants were asked to fill in a four question survey about body balance awareness. This is done for the front crawl as well as the backstroke. After the test they were asked a few questions about the feedback. **Results:** The Relative Average Body Angle (RABA) and the amount of feedback that is or would be administered (TSUT) is calculated for every test phase and compared. For the front crawl a significant difference is measured between the baseline and the feedback phase, and between the baseline and the retention phase, for the the RABA as well as the TSUT. For the backstroke only a difference is found between the baseline and the feedback phase for the RABA. This is likely due to the small amount of participants. The participants reported to be most aware of their body balance in the feedback phase and second most aware in the retention phase. Also, generally the participants reported experiencing the wearable as useful and the feedback as clear. **Findings:** The results show that there is motor acquisition of better body balance. Also, haptic feedback in an aquatic environment generally is perceived and understood by the participants and overall they reported a sense of usefulness. The use of concurrent haptic feedback during swimming can help aid in improving swim training in a significant and novel way.

CONTENTS

1 INTRODUCTION

1.1 Motivation

Competition swimming is a sport with very repetitive movements in which performance can be improved by a relatively large amount by having the right swim technique. However, learning the right swim technique is non trivial. Unlike with sports that are on land, coaches are not able to give feedback about the swimming performance during swimming (concurrent feedback), since the pupil's senses are obscured by the water and body position. Instead they rely on observations during a period of training and giving feedback afterwards (terminal feedback) Also, the coach can often not observe every important detail about the swimmer's movement, partly due the obstruction by the water. There are many studies that go into the use of technology to measure swimming performance for research and coaching [1, 2]. From these review studies it becomes clear that there have been few experiments with implementing feedback while performing the swimming activity, despite learning complex tasks tending to benefit frequent and concurrent feedback [3, 4]. Some studies [5, 6] use concurrent auditory feedback and show improvement in performance after practice with the technology over a control group.
Haptics seem to be promising as a user interface in swimming with advantages above auditory interfaces [7]. Auditory interfaces are less suited for swimming presumably because of the noise from the water flowing past the ears.
Visual interfaces have been used with success as well. A study was done to transmit data from a wristband to the goggles of a swimmer using visible light [8]. The swimmer would receive feedback on whether their stroke rate was too slow or too quick by using an RBG-LED in the goggles. However, research into the motor learning was not done with this implementation. Another study that used visual feedback, made use of hand mounted pressure sensors [9]. The athletes would get direct feedback on their individual strokes from monitors placed on the ceiling and the pool floor. They would stay in place with the help of a generated water current. after a cumulative two hours of training sessions the stroke technique improved significantly. No test on retention was performed. To summarise, since haptics have barely been investigated in swimming before while showing promise [7], and concurrent feedback for motor learning during swimming has also been researched only a few times, an opportunity is presented to research the combination of concurrent feedback in swimming using haptics.

1.2 Context Analysis Questions

To investigate concurrent haptic feedback in swimming a solution must be designed that can actually give this feedback. For that to be realisable, first, knowledge needs to be gained in principles surrounding swimming, measuring in swimming, motor learning using haptics, and wearable design. For simplicity, this report will mainly focus on the front crawl, since this stroke seems to be most researched in relation to measuring [1, 2]. However, the backstroke will also be discussed for it's similarity to the front crawl. The following research questions are defined for this:

1. What is the correct swimming technique of the front crawl and backstroke?

   (a) What aspect of the front crawl and back stroke are indicative for the greatest performance?
   (b) What are common mistakes in learning to perform the front crawl and the backstroke?

2. How can this technique be measured?
   (a) What sensors can be used for measuring swimming?
   (b) How can the measured data be translated into variables that are indicative of performance?

3. How can these measurements be used in combination with haptic feedback to facilitate motor learning of the correct technique?

4. How can a wearable for an aquatic swimming environment be designed?
   (a) Where on the body can sensors be placed to not interfere with swimming?
   (b) What key aspects need to be taken into account?

5. What are the the other systems that make use of concurrent feedback during swimming?
   (a) What methods do they use to give concurrent feedback?
   (b) What are the strong and weak points of these systems?
   (c) What research would add meaningful value to this research space?

1.3 glossary

- ”RABA” : abr., stands for ’Relative Average Body Angle’. This is a measure used to quantify the difference in body balance performance over a certain length of swimming in such a way that it is comparable between participants.
- ”TSUT” : abr., stands for ’Time Spend Under the Threshold’. This is a measure used to quantify the amount of time the body angle was lower than a calibrated threshold. In a test where haptic feedback is turned on, the participant would experience haptic feedback any time the angle is lower than this threshold value.
- ”Front crawl”, ”freestyle” sometimes abbreviated to ”FS” : The most popular swim stroke. It is performed by laying prone in the water and using the arms to push oneself forward.
- ”Back stroke”, sometimes abbreviated to ”BS” : The back stroke is a swimming stroke performed by laying on ones back and propelling oneself forward mostly by using the arms.
- ”Body balance” : A key performance indicator of swimming. This refers to the ability to maintain the correct angle, with regards to the water surface, of one’s own body around the bilateral axis while swimming to achieve the greatest performance. By maintaining the right angle a swimmer can reduce their frontal area increasing their hydrodynamics.
- ”Body angle” : This is the angle of a swimmer’s body around the bilateral axis with regards to the water surface.
- ”Body roll” : This is the turning around the polar axis of a swimmer’s body. This movement is essential for the correct performance of the front crawl and the back stroke.
- ”Free swimming” : Refers to the phase of swimming between the wall push-offs, turns and the underwater phases. Usually, a swimmer spends most time in this phase during a lane. In this phase, the swimmer is performing a swim stroke.

2 CONTEXT ANALYSIS

2.1 Swimming Technique of the Front Crawl

To be able to make a device that helps improve swim technique, correct swim technique will need to be defined. There is no fully defined swim technique that is the best method of swimming for all people due to differences in anthropometric characteristics (physiological makeup, body shape and limb length) [10]. For instance, stroke length is highly influenced by body length, arm span, and size of the hands and feet [11, 12]. Also, the goal between swimmers can differ. A sprinter might define the most efficient stroke as the one where the available energy is put into forward propulsion within a short distance, while marathon swimmers are more interested in an optimal distance per energy expenditure.
Despite these differences, there are best practices which are relevant for most swimmers. For, in the end, the goal of swimming is to efficiently turn physical excursion into forwards momentum.

2.1.1 Front Crawl Characteristics

Engel et al. defined the arm stoke technique of the front crawl into four phases on the basis of phases defined in previous studies [13]: entry and catch, insweep, upsweep, and recovery. In figure 2.1 the phases are represented in a graphical fashion. In these phases the right execution and timing are important. Besides the arm movement the front crawl also consists of the right body roll and balance, leg kick and breathing.

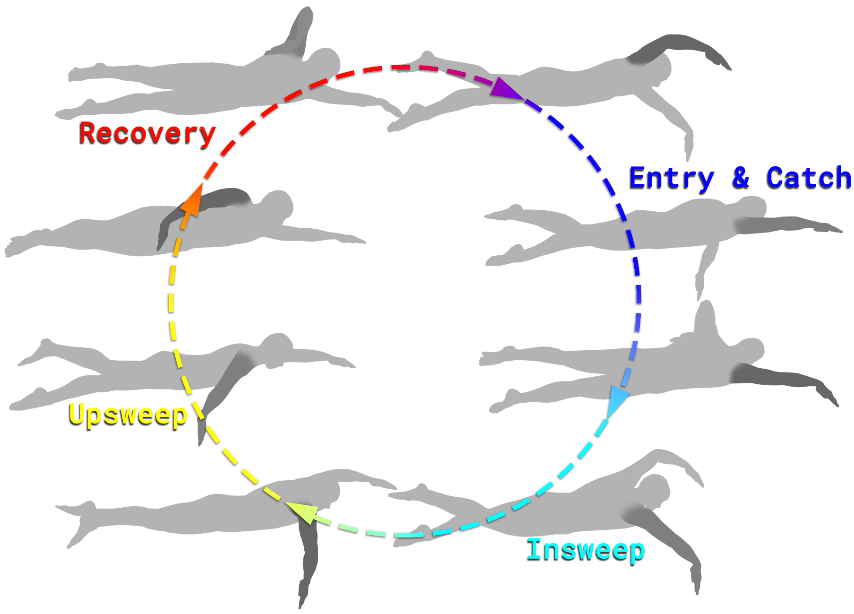


Figure 2.1: Four arm stroke phases of the front crawl.

Entry and Catch

The entry and catch starts when the hand first touched the water, and it ends when the hand is pointed slightly down as a lead up to the insweep. This bend in the wrist is important to increase the time the hand produces forward propulsion. [14].

Insweep

The insweep is the first of two propulsion phases. The phase starts when the catch ends, and is done when the hand reaches a point directly under the shoulders. At this point, the elbow should be bend between 100 and 120 degrees. [15]. This arm position should lead to great leverage on the water without straining the shoulder too much. During the insweep the elbow is kept high and the hand should push backward rather than downward [14]. Placing the hand underneath the shoulder rather then to the sides should allow the swimmer to be propelled forward instead of being twisted along the anteroposterior axis [10].

Upsweep

The upsweep is the second phase that provides propulsion. The upsweep starts where the insweep ends and stops when the hand does not push backwards against the water anymore. Also, in this phase it is important to push the water backward and not upward [16] At the end of the upsweep the recovery should be prepared by not fully extending the arm as the last part of the upsweep provides little extra propulsion [16].

Recovery

The recovery starts when the hand starts moving forward and out of the water and ends when the hand touches the water again at the front. During the recovery a high elbow position is beneficial [10]. By having a high elbow position it means that the center of mass stays closer to the mid-line of the body, keeping side to side stability intact. A high elbow position does not mean that the elbow has to be flexed.

Index of Coordination (IdC)

IdC is an interesting performance metric since it is closely linked to a swimmers speed [17]. The IdC is determined by the time between the propulsive phases (insweep and upsweep) between the arms and the time spend in these propulsive phases. This time is called the lag time. If the IdC is zero the propulsive phases of one arm directly follow up the propulsive phases of the other arm. If there is a delay between the end of the propulsive phases of one arm before the other arm starts with the propulsive phases, then the IdC will be negative. If the propulsive phases of one arm start before the other arm is finished with the propulsive phases the IdC is positive [17]. If a swimmer has a higher IdC that means that there is larger time spend in the propulsion phases and more time is spend gaining forward momentum.

Kicking Technique

It has been in discussion how much the kicking action actually adds to the performance of a swimmer. It is mostly credited for facilitating body balance[10, 18, 19]. It seems though that for longer distances legs might also play a more important role in propulsion [20]. Kicking does not need to happen perpendicular to the water surface. The body rotation that happens causes the legs to kick slightly diagonal which cancels out the tendency of the legs to swing out due to force applied by the arms [10]. The kicking technique should be such that the frontal area of the swimmer is minimized to reduce the drag force against the water [19, 10]. This can be done by having plantar flexed feet while pointing the toes inward. With the upbeat the ankle should break the water surface but not more and with the downbeat the feet should not get too low [19, 18]. Usually the front crawl is performed with a six-beat kick. That means that each leg goes up and down three times per full arm rotation. However, it is possible to use a two beat kick to save energy in longer distances. This is rarely recommended though [21] because it requires a specific swim-style and it only benefits a swimmer whose arm technique is already well established.

Body Roll and Balance

While performing the front crawl the upper body will rotate along the vertical axis and, to minimize drag, laying parallel to the water surface is beneficial. The body roll facilitates the arm movement. A trained swimmer's body roll looks sinusoidal [10, 22]. Rotation in the shoulders is greater than rotation in the hips [23, 22]. The body roll that is taught by coaches is nowadays between 45 and 60 degrees. Going further than this could cause the legs to open up in the horizontal plane, creating drag [21]. Some people show asymmetry in their body roll (rolling further to one side than the other). There is no conclusive evidence that this has an impact on performance [22].

2.1.2 Common Mistakes

An interview was done with eleven swim coaches for a PhD thesis in which the interviewer asked for the most crucial faults in front crawl swimming and for which of these faults technical support would be appreciated [24]. The results of this research can be seen in table 2.1 and 2.2. A graphical representation of the faults can also be seen in figure 2.2 From these results it seems that the most import issues to tackle are: No continuous movement, large variation in velocity and; 'Bad' body balance, head too high, legs too low. However, an argument against these results is that the coaches that are asked these questions are from a similar region with maybe a different teaching philosophy compared to coaches from different regions. Besides that these findings are still based on opinion rather than empirical evidence. These results will hold more ground if they can be repeated in a different region. That being said, these do give a good indication for solving swimming issues with a wearable, these results can be used to find the best variables to measure.

Swim style fault \ cruciality	high							low	
	1	2	3	4	5	6	7	8	mean
'Bad' body balance, head too high, legs too low	4	5	1	-	1	-	-	-	2.0
No continuous movement, large variation in velocity	3	2	2	3	-	-	-	1	3.0
Leg kicks not initiated by the hips, knee is bend too much	1	1	5	-	3	1	-	-	3.5
Insufficient body rotation	2	1	1	2	1	3	1	-	4.1
'Bad' arm position under water, elbow too low	-	-	2	3	3	-	3	-	4.9
Skewing of upper and lower body when breathing	1	1	-	1	1	2	2	3	5.6

Hand entering too far in the middle or on the opposite side	-	1	-	1	1	2	3	3	6.2
Breathing is non-periodic	-	-	-	1	1	3	2	4	6.6

Table 2.1: Survey result adapted from Marc Bächlin's PhD thesis[24]. The asked question was: *"Which fault do you consider as most crucial for fast and efficient crawl swimming?"* The importance value is denoted is the top row, with the count of how many times a response was for that specific importance value in the rest of the table. Eleven coaches from the "Schwimmverein Emmen" and the "Schwimmklub Luzern" answered the question.

Swim style fault \Desire for additional help	high						low		
	1	2	3	4	5	6	7	8	mean
No continuous movement, large variation in velocity	5	3	2	1	-	-	-	-	1.9
'Bad' body balance, head too high, legs too low	-	5	2	3	1	-	-	-	3.0
Skewing of upper and lower body when breathing	2	1	3	1	1	1	2	-	3.8
'Bad' arm position under water, elbow too low	-	2	2	3	2	1	1	-	4.1
Leg kicks not initiated by the hips, knee is bend too much	2	-	2	1	3	2	-	1	4.3
Insufficient body rotation	2	-	-	1	2	3	2	1	5.1
Hand entering too far in the middle or on the opposite side	-	-	-	1	1	1	4	4	6.8
Breathing is non-periodic	-	-	-	-	1	3	2	5	7.0

Table 2.2: Survey result adapted from Marc Bächlin's PhD thesis [24]. The question asked was: *"Which fault would you be most happy to be supported by any additional help, because it is difficulty of detecting or continuously supervising this fault?"* The importance value is denoted is the top row, with the count of how many times a response was for that specific importance value in the rest of the table. Eleven coaches from the "Schwimmverein Emmen" and the "Schwimmklub Luzern" answered the question.

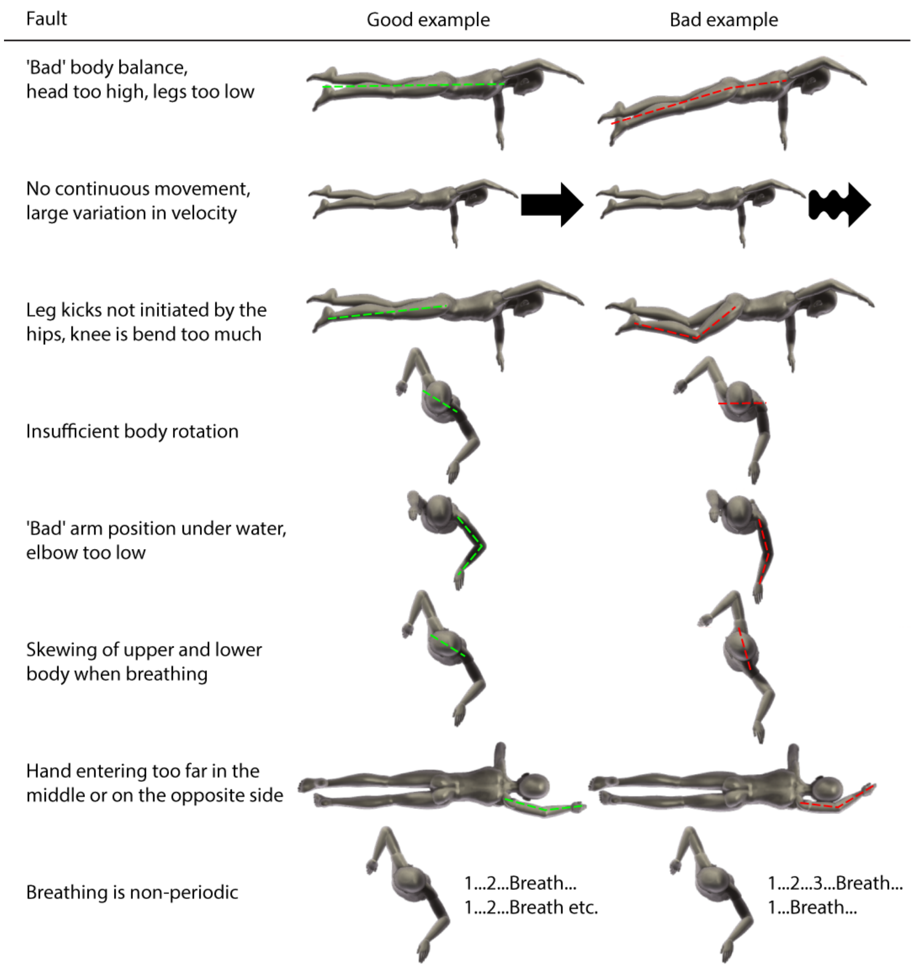


Figure 2.2: Graphical representation of common faults made during the front crawl

2.2 Swimming Technique of the Back Stroke

2.2.1 Back Stoke Characteristics

The same four phases that are present in the front crawl can also be seen in the backstroke. A graphical representation of the four phases of the backstroke can be seen in figure 2.3.

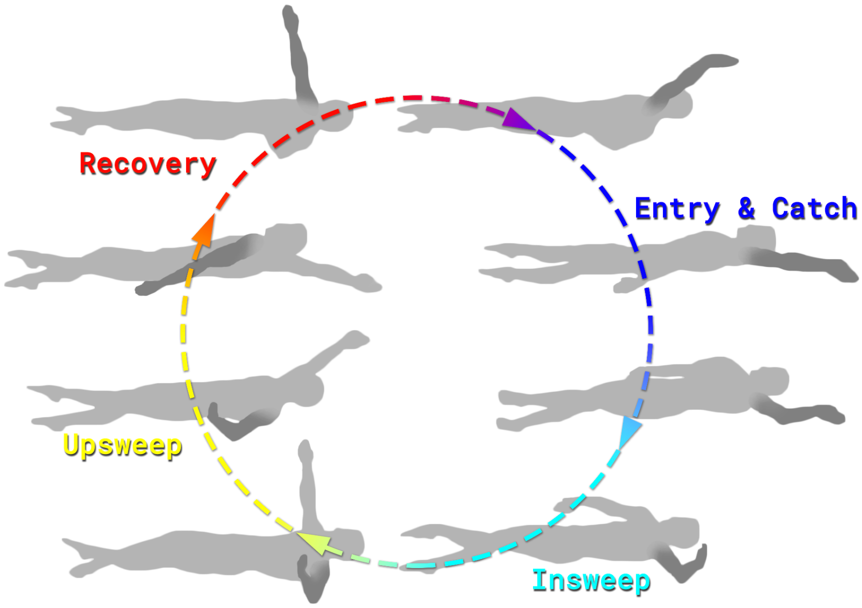


Figure 2.3: Four arm stroke phases of the backstroke.

2.2.2 Common Mistakes

In a previous study 20 experts were asked to rate a list of 42 common mistakes in backstroke swimming on a 7 point scale of importance [25]. The highest rated mistakes, with a median of 7, were in no particular order: bicycle kicking, asymmetrical kicking with one leg aside, the feet are not extended, sitting position, incorrect timing of kicking and armstroking, and push water to the side during the armstroke. Unfortunately no report on how common these mistakes are were found.

Index of Coordination (IdC)

The role of the IdC in backstroke swimming is found to be not as important as it is for front crawl swimming [26]. This is likely due because it is limited, mostly by the shoulder flexibility, i.e. the ability to rotated the arms behind the back. That being said, this is a study done with elite swimmers. Beginners can struggle with keeping the IdC high enough [25].

2.3 Measuring in Swimming

This chapter will go over measuring techniques in swimming. It is mostly focused on measuring using inertial measurement units (IMU), because of the versatility of such devices. Finding a good variable to measure and a reliable way of measuring said variable is essential to making a working prototype that gives feedback on your swimming. After all, a device can only give feedback on what a swimmer is doing is if the device has data on what the swimmer is doing.

2.3.1 Methods of Measuring

The golden standard in swimming performance analysis is video analysis [27]. However, the problem with video analysis is that the annotation of video data costs a lot of time and effort which keeps it from being used as a feedback tool. Other novel methods have been used to measure aspects of swimming. For instance the use of pressure sensors on the hands [6, 9], a pressure sensor on a buoy that is being dragged along [6] and the use of magneto sensors [28].

Inertial measurement units, like gyroscopes and accelerometers, are often used in swimming, presumably because of the low cost and ease of implementation[1, 28]. These sensors can also be found back in commercial fitness tracker solutions as, for instance: the Apple Watch [29], the Garmin swim [30], the Mi-band [31], Samsung Galaxy Fit [32] and smart swim goggles [33, 34]. These commercial solutions do not give much information on how the sensors are used to produce meaningful data.
There are different phases that occur during pool swimming. These can be defined as: Wall push-off, Glide, Strokes preparation, Swimming, and Turn [35]. These strokephases are represented in figure 2.4 Mostly, studies have focused on the free swimming phase [1] but other phases also have a big role to play in overall performance [36].

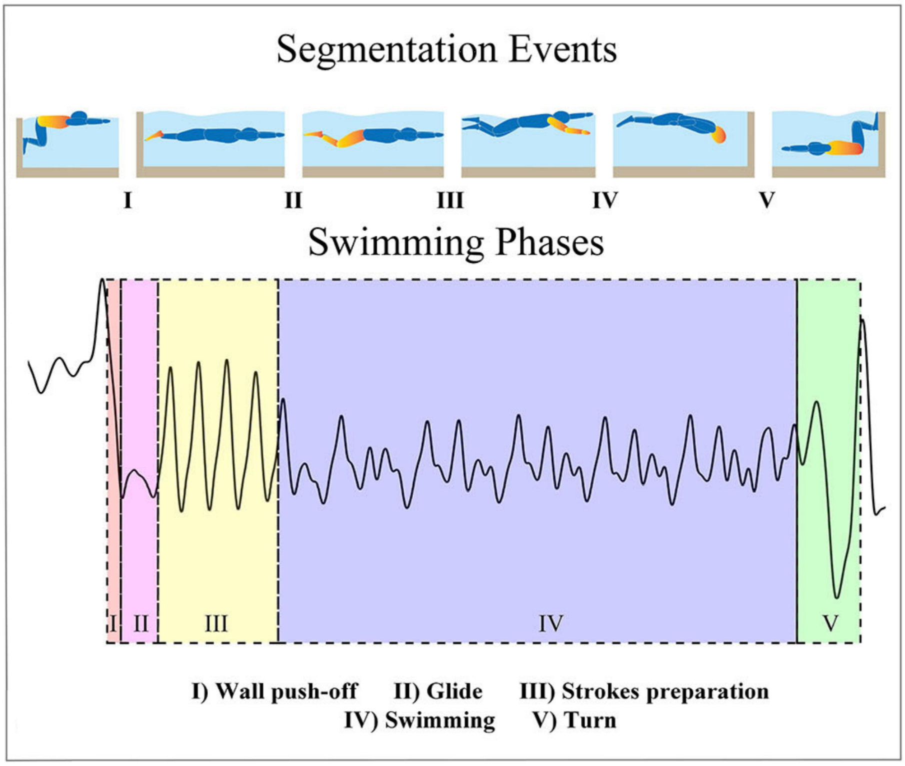


Figure 2.4: Figure is originally from Hamidi Rad et al. [35]. It includes a graphical representation of the swimming phases as defined by Hamidi Rad et al. and a graph of plotted IMU data of a swimming bout with the different phases being highlighted. The phases can be described as follows: 1) The wall push-off phase starts when the swimmer first experiences forward motion when the feet are against the pool wall and ends when the feet leave the pool wall. 2) The glide phase is the phase after a push off when the swimmer is under the water surface and not moving upper and lower limbs. 3) Stroke preparation starts with underwater kicking and ends when the first stroke cycle is finished. 4) The swimming phase is when the stroke cycles are performed. 5) The turn phase starts when the turn is initiated and ends when the push-off phase starts.

2.3.2 Variables in Literature

Many different variables have been measured in literature using an inertial measurement unit. Mooney et al. [1] have done an analysis on the IMU's in swimming during the years 2000-2015. They published a table with different sources and what output variables those sources measured. An adaption of this table can be found in appendix E. From this was derived which output variables were used most in those sources.

The most common output variables are: stroke count and stroke rate, stroke identification, velocity, lap count and lap time. These examples of variables individually do not directly describe the quality of swimming technique however, improvement in these variables can indicate an improvement in performance. Besides, the methods for attaining these variables could be used for attaining different variables. To correctly determine the value of these variables it is best to analyse them during the swimming phase when these actually occur. For example, strokes only occur in the free swimming phase so it would be counterproductive to analyse the rate of strokes during the other phases. Hamidi Rad et al. [35] have proposed a method of extracting this information, however they did not make clear how this can be done in a real-time fashion.

Stroke Count and Stroke Rate

The stroke count is the amount of strokes that are made and the stroke rate is how quickly the strokes are performed. Both of these variables can be determined if there is a record of when the strokes have occurred. Davey, James and Anderson [37, 38] determined the stroke rate from an accelerometer placed on the lower back. This was done by isolating the free swimming phase, then the the mean is taken from the acceleration data from the bilateral axis. The peaks above the mean correspond to a left hand stroke and the peaks below correspond to the right hand strokes. These peaks were determined using a peak detection algorithm. Le sage et al. [39] developed an algorithm that works in real time by first low pass filtering the signal with a Butterworth filter and counting the zero crossings around the mean value. Andreoni et al. [40] did something similar to davey et al. but with the accelerometer higher up the back . Ohgi [41] used a wrist mounted sensor and determined that the collision between the swimmer's hand and the water surface showed a peak in the X and Y axis.

Stroke Type Identification

Within competition swimming there are four different strokes: Frontcrawl, Backstroke, Breaststroke and Butterfly. Determining the type of stroke can be useful for recording training sessions or to do further analysis on the stroke, since every stroke needs different methods of determining their specific characteristics. Topalovic et al. [42] devised a method of determining the stroke with a IMU on the wrist of the swimmer that could be used in real time. This was done by setting threshold values for the average and maximum accelerations of the different axis of the accelerometer. These values were determined by trial and error and they claim an accuracy of 99%. However, no statistical analysis is shown for this. Ohgi, Kaneda and Takakura [43] used a chest mounted accelerometer and let 45 college students swim the four different competition strokes to record their movement data. Using a multi-layered neural network and a decision tree, the authors managed to get a correct recognition rate of 91.1%. This figure can potentially be even better if the authors would also have recorded gyroscope data and used it in their classification, since is it probable that some strokes are more identifiable with the additional angular acceleration data instead of solely linear. Something that is interesting, is that the machine learning algorithms they have used seem to have to most trouble distinguishing between backstrokes and breaststrokes. While, evident from their data, the orientation of the swimmer is all that needs to be known to classify a backstroke correctly, which is represented in the mean of the z acceleration. If this is positive, the swimmer swims on their back and if it is negative, the swimmer swims on their belly. Using this one simple and cheap calculation the recognition rate ought to be able to improved significantly.

Velocity and Distance

Dadashi, Millit and Amanian [44] made use of an accelerometer strapped to the arm of the swimmer. The velocity could be determined by using strap-down integration of the angular velocities to work out the displacement in 3D space for each instance. By averaging the velocity of the displacement they can make a decent estimation of the overall velocity of the swimmer. Beanland et al. [45] simply made use of a GPS sensor placed on the head of the swimmer to calculate the velocity. Bächlin and Tröster [46] made use of the known length of the pool. By taking the time it takes to complete a lap, the average speed of the swimmer can be calculated.

Lap Detection

A method of detecting laps for a sensor placed on the lower back is by measuring the acceleration and setting a threshold for the highest peaks, since the highest acceleration occurs when pushing off from the wall [35]. With turns where the swimmer rotates allong an axis a simple zero-crossing algorithm can be used [47]. This does depend on the sensor placement as well.

Body Balance

A different more novel variable which has been measured is the body balance, or the pitch angle of the swimmer [48]. Two different sensor placements were tested for this: one on the upper back and another on the lower back. To get an angle from the accelerometer the following equation was used on the accelerometer data: $\beta = -arcsin(x_b/1g)$ where β is the body angle in degrees, the x_b is the acceleration vector along the vertical axis of the body, and the g is the gravitational constant. On the hand of video annotation the effectiveness of measuring the correct angle for both sensor locations were determined where the upper back sensor seems to very accurately correlate with the actual body angle.

2.3.3 Sensor Placement

The most common places to put IMU's are on the wrist or on the lower back [1], but other locations like the upper arm, chest, upperback, or somewhere on the lower limb have also been used. Depending on what needs to be measured different locations might be chosen. For measuring the stroke rate of count, many different locations can be suitable. Since strokes are performed cyclically, if it is possible to discover a reoccurring pattern in the data it is likely to be at the frequency of the stoke rate. For measuring velocity using the integration of the acceleration data it might be more useful to pick a sensor location that moves relatively little to avoid drift problems. Good locations for this might be on the torso or the head. For measuring kick rate or timing there is not really another option than to place the sensor on the lower limps. A researcher might want to choose to use more than one IMU one a single body location. For instance, to be able to measure the IdC of a swimmer relative spacial information needs to be known of both arms. This is probably impossible to do by using a single sensor. Bächlin and Tröster [46] placed four IMU's on a swimmer, on the upper back, lower back, left wrist and right wrist. The potential cons of using more sensors are that the sensors might interfere with swimming, and that the complexity of the signal analysis increases. Pansiot et al. [49] has done research into different sensor placements and which placement would be suitable to acquire which variable. The adapted table they published can be seen in table 2.3.

Technical Considerations

To measure swimming with an IMU several things should considered from a technical standpoint. Sample rates vary widely in literature, sample rates between 5 Hz [50] and 500 Hz [51] can be found. Choosing a sample rate probably relates more to what the available hardware is capable of and what specific information needs to be extracted from the sensor data. Data probably needs to be stored on the measurement device itself, since it is difficult to send data wirelessly to the side due to the aquatic environment and tethered data transfer would likely

Stroke	Feature	Head	Trunk	Arms	Legs
All	*Lap count and timing*	++	++	++	++
All	*Overall momentum*	++	++	-	-
FC	*Stroke count*	+	+	++	-
BaS	*Stroke count*	-	-	++	-
BrS, Bf	*Stroke count*	++	++	++	++
FC, BaS	*Body roll*	+	++	-	-
FC	*Breathing patterns*	++	+	-	-
FC, BaS	*Arm anti-symmetry*	-	-	++	-
BrS, Bf	*Arm Symmetry*	-	-	++	-
FC, BaS	*Leg anti-symmetry*	-	-	-	++
BrS, Bf	*Leg symmetry*	-	-	-	++

Table 2.3: Table of possible sensor locations for measuring certain variables (adapted from Pansiot et al. [49]). Acronyms and symbols stand for: front crawl (FC), backstroke (BaS), breaststroke (BrS), butterfly (Bf), directly obtained (++), possible to estimate (+) and not available (–)

interfere with the free motion of the swimmer. For this a micro-SD card of 1 Gigabytes or more would in most cases be sufficient. The measurement device needs to be sealed against water ingress. Many different methods of sealing such a device are proposed in literature without any clear indication of a ”golden” standard [2].

2.3.4 Wrap Up

There are methods that make it possible to measure a swimmers performance. Simple algorithms such as peak detection and zero crossing detection are often used, but there are also examples of the use of machine learning and modelling the motion from the angular velocities. The more complex and computationally heavy a algorithm becomes the less likely it can be used in a real-time fashion. For giving real-time feedback on swimming technique it is thus important to find a variable that can be determined by these simpler algorithms. A good method of finding such a variable is to fail quickly and try many different approaches using a platform that is relatively easy to adapt. The literature can be used as an inspiration. However, many different methods are used to get to the same point, so being open for novel approaches might be very lucrative in this field of study.

2.4 Motor Learning with Haptics

There are different forms of augmented feedback that can be used for motor learning. In theory, all human senses could be used for providing feedback. However, gustatory (taste) and olfactory (smell) feedback are difficult to technologically augment, so these are not often used. In swimming context, visual [7, 8], auditory [7, 52, 6] and haptic feedback have been used [7]. For this report the focus lies with haptic feedback since there hasn’t been much research about haptic feedback in a swimming environment but the research that has been done shows some promise [7].
Haptic is defined by El Saddik et al. as:

> The science of applying tactile, kinesthetic, or both sensations to human–computer interactions. It refers to the ability of sensing and/or manipulating objects in a natural or synthetic environment using a haptic interface [53, p. 5].

From this definition that would mean that haptic feedback is feedback that concerns tactile and/or kinesthetic sensations.

2.4.1 Forms of haptics

In [4] three types of haptic feedback in motor learning are described: haptic rendering, in which a computer model with force information is used to actuate a haptic interface; robot-assisted training and rehabilitation, in which a robot/mechanical structure guides a user through a motion or resists the user from a certain motion; and haptic augmented feedback, in which haptic interfaces are used to are used to give information on a situation or performed action with the goal of improving an action. This report will focus on the latter one since building a swimming simulation or robot falls out of the scope of this research.

Different haptic interfaces can be used for augmented feedback. Often these interface work with vibration motors. There are two common types of vibration motors: Linear Resonant Actuators (LRAs) and Eccentric Rotating Mass motors (ERM motors). LRAs make use of a voicecoil to move a mass that is connected to a magnet to create vibrations [54]. ERM motors have a mass that is off axis from the motors axis to create vibrations [55]. According to [56], making a vibratory display works very well in a lab setting on the lower back and several patterns could be distinguished. It also works on the lower arm in a lesser extent. This study shows that it is possible to convey relatively complex information using a vibratory display. Whether this principle also works within an aquatic sports environment is not yet clear. Another method of conveying more information using haptic displays is by using more than just a vibratory modality. The VPS display uses a combination of vibration, pressure, and shear to increase the complexity of tactile information [57].

2.4.2 Motor learning complex and simple tasks

A lot of research into motor learning is done in lab environments and with the use of simple tasks [58, 59]. These are tasks which generally require relatively few different muscles and have a simple goal, or how Wulf and Shea define it: ”Tasks will be judged as simple if they have only one degree of freedom, can be mastered in a single practice session, and appear to be artificial.” [3, p. 186] It seems that the principles derived from these simple motor task rarely translate to more complex tasks [3]. It does seem that more complex tasks generally need more frequent feedback [3]. It is important though to find a balance in the amount of feedback that is given. For example, in a study where participants learned to putt a golf ball, the group who got to see where their golf ball ended only a third of the time managed to score better on retention test than the group who got to see the result of their hit every time [60]. It is unclear what mechanism is responsible for this result, but it is hypothesized that it could have to do with the guidance hypothesis [61], where learners depend too much on the external feedback to develop internal feedback mechanisms. Another explanation might be that learners how got denied feedback focused more intently on their own movement, which could be beneficial for performance.

2.4.3 Feedback content and timing

If feedback is not given in a timely matter the participant might not understand what the feedback is being given for. There is also a difference between giving feedback as the activity is being performed (concurrent) or afterwards (terminal). Another thing to look out for is what the actual content of the feedback is. Too much or irrelevant feedback may leave the receiving participant confused.

For implementing feedback technology three criteria were proposed by Anderson [62] for the feedback technology be effective. Phillips et al. [59] make some additions to the first criterion. Together they make the following list:

1. The feedback should be accurate and relevant
    (a) The chosen variable should be a key variable in performance improvement
    (b) The chosen variable should be accurately measurable
    (c) The chosen variable should be adaptable by the athlete receiving the feedback
2. The feedback should be appropriately timed and delivered
3. The feedback should be decipherable by the athlete.

Accurate and Relevant

For the first criterion, being accurate and relevant, to be met an understanding is needed of the discipline of swimming. This understanding is needed to be able to define the right variable. An example of a variable that meets all of Phillips and colleagues' criteria is swimming velocity, since: it is the key variable of performance, it has been measured accurately [6, 44, 45, 46], and the athlete can adapt it.

Appropriate timing and delivery

The second criterion is about appropriate timing. In learning to swim, it is traditionally only really possible to get feedback after performing a bit of swimming. Having feedback on a mistake as soon as the mistake happens could result in better understanding of the mistake, especially because in swimming there are a lot of precise movements to focus on that could distract from where and when the fault is made. To make feedback 'feel' real time, the latency between the action and the feedback should not exceed 50 milliseconds [63] with haptic interfaces.

Decipherability

Criterion three should be achieved with good wearable design. Finding a good intuitive metaphor for vibrotactile feedback is believed to be imperative [64, 65]. Furthermore, appropriate locations on the body should be found for giving the vibrotactile feedback, since some places are more perceptive to vibrations and do not hinder movement. Also, some locations are initially advantageous for being in line with where to expect feedback. It seems however that this advantage does not hold on if the user gets used to less intuitive sites [66]. Other things that should be considered are appropriate signal ranges and modulations [67] and polarity [68, 64, 65]. Vibrations can mean to move towards them of away from them. Polarity preferences can be very much individual [65].

Practical examples

Chollet, Madani and Micallef have used the velocity variable to give concurrent feedback [6]. Their solution required a buoy that dragged behind the swimmer and the swimmer received an audio signal of which the pitch corresponded to the speed. This solution seems to meet the other criteria as well since the athletes could change their technique immediately when getting the feedback and the metaphor used is a simple to understand one. This is confirmed by the results which seem to show that the solution worked well; the groups that received the augmented feedback performed better than the control group after several training sessions over 15 days. However, this solution was not tested in isolation (the test was done in combination with pressure sensing paddles) Also, since there has been some technical advancement in miniaturization of electronics, this solution can likely be made smaller and more elegant.
Another example that seems to adhere to these criteria is the system by Jefferies, Jefferies and

Shawn [9]. Their system involves a set of pressure senors that are worn on the hands and monitors at places that are well visible for the swimmer. A machine that makes a controlled water current made sure the swimmers would stay in the same place while swimming. The monitors would show the pressure curve of the sensors which could then be optimized by the athlete. Because this form of feedback is a bit less intuitive the method of interpreting the curve was explained before the start of the experiment. They admit a few flaws in their method of determining the effectiveness of their system, mainly the low participant number of two. However, for those participants, the results seem to show significant progress in a short period of time (20% in a cumulative time of 2 hours).

2.4.4 Wrap Up

For the goal of teaching swimming with haptic feedback, it makes most sense to choose for an augmented haptic feedback approach (rather than haptic rendering or robot-assisted training) since this is quickest to be implemented and thus has the most potential to find the biggest flaws with using haptic feedback for swimming the fastest.
Swimming is a complex task, and has different pitfalls as compared to simple tasks [3]. Notably, differences in the amount of feedback that should be given. That being said, a lot of principles are not consistent across literature when it comes to motor learning in general [4]. The specific implementation for augmented motor learning used for this project can likely have different best practices than other implementations. Thus, when testing the effectiveness of an implementation of motor learning it is important to take into account how the amount of feedback and the knowledge of results might affect the learning rate and retention. Actually testing the influence of these variables does take a lot of time which might be out of the scope of this research.
The list of criteria from Anderson and Phillips [62, 59] gives a good overview of the most important aspects of designing a suitable feedback system for motor learning. Making sure that these criteria are met already increases the viability of the research.

2.5 Wearables

2.5.1 Requirements wheel

in literature, several requirements have been discussed for wearables. However, often human factors are overlooked [69]. Often design requirements can be broken up into several parameters. For instance, 'The wearable has to be comfortable' can be looked at from different parameters like: shape, breathability, hygiene, temperature, sizing, obtrusiveness, weight and movement. Defining the requirements to be more focused can prevent overlooking them. To design a good wearable, physical, cognitive and emotional ergonomics should be taken into account. The wearable design requirements wheel (see figure 2.5) as proposed in [69] can be used to define the right requirements in applications of concurrent feedback in swimming.

2.5.2 Wearability in Swimming

There are several things that are different for an aquatic environment (during swimming) as compared to a terrestrial environment. For safety and durability it is for instance important to have the device watertight so that no short circuit occurs. Because of the viscosity of water it is also more important to make the wearable aquadynamic as opposed to making an aerodynamic wearable in air. In [70] different sites on the body were discussed for wearables based on previous research. However, the studies that were referenced mainly focused on terrestrial use of wearables. For instance, the heat map for comfortable weight distribution does not apply at all during swimming, due to buoyancy and different body position compared to the gravity. What

Figure 2.5: Wearable design requirements wheel from [69]

might still be quite similar for aquatic as well as terrestrial environments are the sites that are sensitive for passive touch. The heat map for this can be seen in figure 2.6. This figure mainly shows how precise the touch can be and not what the smallest actuation force is that people can feel. This figure is thus more useful for showing where higher resolution haptic interfaces can be located as opposed to where people can still perceive haptic interfaces.

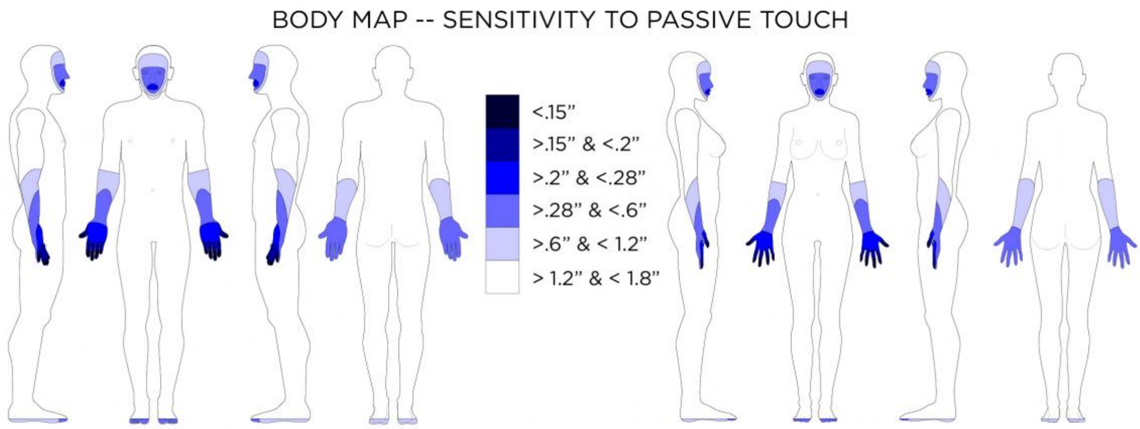


Figure 2.6: A body heat-map for the average distance in two-point discrimination sensitivity test on body locations. Heat-map created by Clint Zeagler [71]

2.5.3 Requirements

A list of requirements can be made based on the requirements wheel (figure 2.5) and with an aquatic environment in mind. For this project it will however be most important to make a proof of concept, not necessarily a product for people to buy or be enticed by.

- The swimming wearable must:
  1. be sufficiently water tight to go swimming with. (safety, durability)
  2. be able to reliably measure a variable that indicates something about swimming technique. (reliability)
  3. give haptic feedback based on a the swimming technique of the swimmer. (usability)
  4. not interfere with front crawl swimming movements. (comfort, safety, usability)
  5. not cause pain or discomfort while wearing. (comfort)
  6. have at least enough battery to work for 200m of swimming. (reliability, usability)
- The swimming wearable should:
  1. give an indication on the power- and recording state of the device. (usability)
  2. be able to record movement information that can be retrieved for further analysis. (usability)
  3. have one or more easily accessible buttons to interact with the device. (usability)
- The swimming wearable could:
  1. look sporty and cool. (aesthetics)
  2. be quick to put on and take off (usability)
  3. look nice when worn (engagement)

2.6 State of the Art

In this section, similar systems for feedback during swimming are evaluated and the strong and weak points of their respected studies summarised. The criteria set for the systems to be handled in this section are that the system must give concurrent feedback (as the action is happening) on swimming and it does so based on a variable measured from the swimmer. Five different methods where found that fit this description. The first three systems give auditory feedback and the other two give visual feedback.

2.6.1 Stroke Informative Paddles

The stroke informative paddles is a system that makes use of pressure sensitive hand paddles that would produce a sound at the moment a certain threshold pressure was reached [72]. In figure 2.7 a schematic drawing of the wearable and its use is shown. The swimmer would hear this through the use of headphones. This system was tested first in isolation [72] and later in combination with the system for capturing instantaneous speed variations of the swimmer's movement discussed in the next subsection [6]. In the first test this system was tested with 34 participants and showed a significant improvement in the swimmer's performance when using the informative paddles as opposed to dummy paddles. Both the stroke count and swim time over 300m decreased. The second test took place over a period of 15 days with 4 training sessions the first 4 days and a test moment on day 1, 5, and 15. The test group consisted of 58 swimmers. It seemed like there was also a significant improvement when this system was used in conjunction with with the speed variation system and this improvement persisted after 15 days.

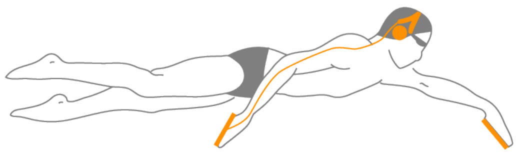


Figure 2.7: Paddles that provides binary auditory feedback on the pressure exerted on the water with the hands [72].

2.6.2 System Capturing the Instantaneous Speed Variations of the Swimmer's Movement

This system makes use of a pressure sensor that is dragged by the swimmer through the water [6]. This pressure is directly correlated to the speed of the swimmer. The pressure is fed back to the swimmer as an audible pitch, this way variations in speed can be heard as changes in pitch. In figure 2.8 a schematic drawing of the wearable and its use is shown. This system was tested in conjunction with the stroke informative paddles [6]. The best results were measured from this test when first this system and then the systems combined were used for the training.

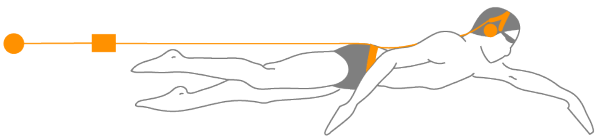


Figure 2.8: System with a pressure sensor and a buoy for giving continues auditory feedback on the instantaneous speed variations of the swimmer [6].

2.6.3 Sofiswim: The Sound of the Underwater Dolphin Kick

This system makes use of an IMU to measure the vertical acceleration (up and down motion) of the hips during the underwater dolphin kick [5]. This acceleration was made audible both in a discreet and continues fashion and fed back to the swimmer trough the use of earphones. In figure 2.9 a schematic drawing of the wearable and its use is shown. This wearable was assessed in a qualitative manner with a total of 9 participants. From this test the participants reported becoming more aware of relevant aspects of the underwater dolphin kick. They preferred also a discrete auditory signal, with one pitch describing the maximum acceleration per cycle, above the continues auditory cycle, with a pitch that was modulated by the acceleration. Both signals were deemed as meaningful feedback by the participants.

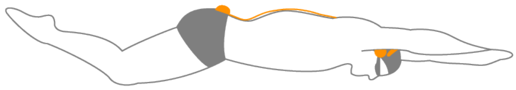


Figure 2.9: Wearable with IMU that measures the up and down acceleration of the hips during the underwater dolphin kick and converts that to continues or discrete, auditory feedback [5].

2.6.4 Stroke Rate and Heart Rate Visualising in Goggles

This wearable makes use of an RGB LED that is located in the swimming goggles that can display if the swimmer's stroke rate is equal, higher or lower than a set stroke rate. It does this through displaying a different colours [8]. In figure 2.10 a schematic drawing of the wearable and its use is shown. This research was mostly focused on the technical implementation of a sensor on the wrist and the wireless transmission of data trough visible light. Therefore no statements were made about the effectiveness of this implementation of concurrent visual feedback. There are two similar commercial products that make use of concurrent visual feedback through a heads up display in the goggles: the FORM smart swim goggles [33] and the FINES smart goggle [34]. These can display your current stroke rate and split times. The FORM can also use an add-on to show the current heart rate. However, no qualitative or quantitative tests of the effectiveness of these concurrent feedback implementations was found.

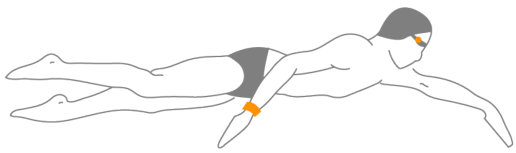


Figure 2.10: A wearable consisting of two parts: an LED in the goggles that gives discrete visual feedback on the stroke rate and a wristband with an IMU that measures this stroke rate and transmits that to the goggles using visible light [8].

2.6.5 Real Time Feedback from the Aquanex System

This is a system for concurrent, visual feedback on the pressure curve exerted on the water [9]. It makes use of the Aquanex system [73] to measure the hand force during strokes. The swimmer is kept stationary by the use of an artificially induced water current, and is thus able to see a screen that shows the pressure curve of the hand whilst performing the back stroke. In figure 2.11 a schematic drawing of the wearable and its use is shown. The system was tested over 4 days with 4 participants who all received a combined training time of 2 hours. In that time, a speed increase for the swimmers was measured due to more efficient strokes, and one of the participants increased their personal record on the 100m backstroke with 4 seconds to 1:12:82.

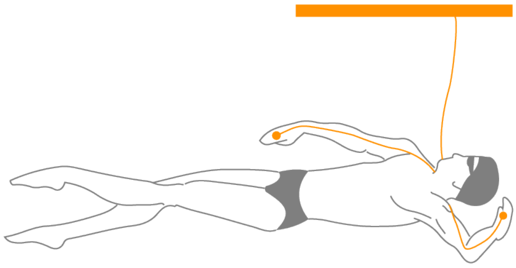


Figure 2.11: A system that makes use of a pool with induced water current to keep the swimmer in one spot, pressure sensors on the hand to measure the force exerted on the water during swimming, and a screen that gives continues, visual feedback on the pressure curve of each stroke [9].

2.6.6 Overview of the Space of Concurrent Feedback During Swimming

The space of concurrent feedback during swimming is relatively small. Only two commercial implementations were found [33, 34] despite most experiments in this space show implementations being effective or promising. However, this can also be due to publication bias. The systems discussed in sections 2.6.1, 2.6.2 and 2.6.5 all made some statement about the improvements on performance [72, 6, 9]. Although the system from section 2.6.5 lacked a control group and only had a test group of four participants, it did show a large improvement in a short period of time [9]. The system in section 2.6.3 was also well rated under its participants.
Even though, from these studies it seems that concurrent feedback during swimming has proven to often lead to positive results, no studies have been found that make use of haptic feedback. This might just be a coincidence, given that merely five systems have been found in scientific literature developed by four research groups. Previous research has shown that haptic feedback in a swimming environment [7] is able to be implemented and participants reacted more readily on haptic feedback as compared to auditory feedback. With haptic feedback it is also possible to measure on different locations on the body than the head without needing to have wires going towards the head or using experimental wireless transmission methods for in the water. That is why concurrent, haptic feedback during swimming is an interesting topic to explore and can be a good addition to this limited space.

2.7 Hardware Exploration

2.7.1 Case Design

In [2] several papers were reviewed that needed to make their swimming sensor watertight for use in aquatic environment. They made a table describing the different methods used to make the hardware suitable to swim with in which it becomes clear that there is no standard method of sealing technology for research during swimming. So instead a box was made from own intuition of how to make it watertight. A simple box was 3D printed with PETG and then silicone was poured in using another 3D printed block on top to ensure there is a cavity for the electronics to sit in. The result is a box with a 5mm thick lining of silicone (see figure 2.12). The lid was made concave and also some silicone was poured in to make a seal with the silicone lining of the case. The whole thing was closed up using 10 m3 screws with threaded inserts in the case. To test if the case suffers from water ingress, a few people were asked to play around in the pool and dive with it. Afterwards the inside of the case was thoroughly visually inspected on signs of water.

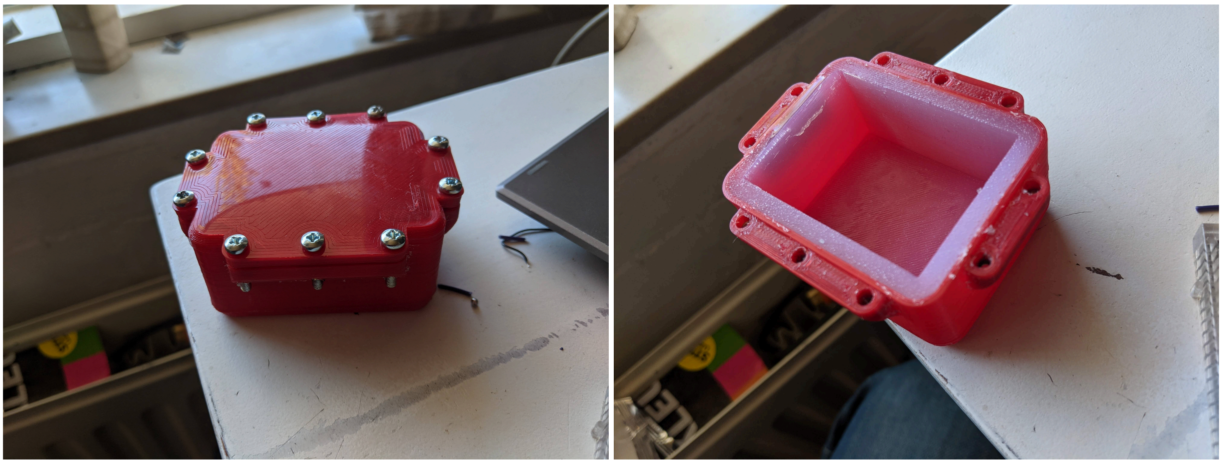


Figure 2.12: Water tight casing prototype with and without lid. Made from 3D printed PETG, silicone, brass threaded inserts and 10 M3 screws

2.7.2 Electronics and first readings

The IMU that was used for the first reading was the MPU6050. This was read out by an Raspberry Pi Pico powered by a rechargeable battery. The sensor data were stored on the internal memory of the Pico itself. An overview of the electronics setup can be seen in figure 2.14. The code that was used can be found in appendix A. In figure 2.13 a picture can bee seen of the fitted electronics. Before putting the electronics in the case, it was first tested for robustness and water-tightness. This was done by putting a piece of toilet paper in the case and giving it to some friends that where instructed to play around with the case in the pool. upon receiving the case again I checked the inside for any droplets of water and or a sign of wet toilet paper. No sign of water in the case or significant damage to the case was detected. 2.13).

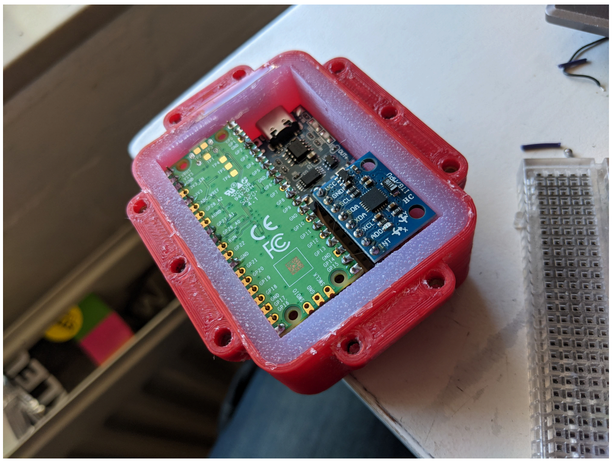


Figure 2.13: Electronics fitted inside of watertight case

The electronics were turned and the case with electronics was placed in the swimming trunk in the back. The output data from the IMU of the four lanes of swimming in figure 2.15.
This is a section of data that started being recorded before getting to the swimming pool. Since the on/off switch is within the housing of the wearable. From the repeating patterns it is safe to assume however that this is swimming. The bigger peaks in the accelerometer data look like the places where the turning takes place. The gyroscope data clearly shows that in the first lane the angular acceleration around the y axis is larger than around the x axis and in the consecutive lanes it is the other way around. this is so likely because of a different stroke. It

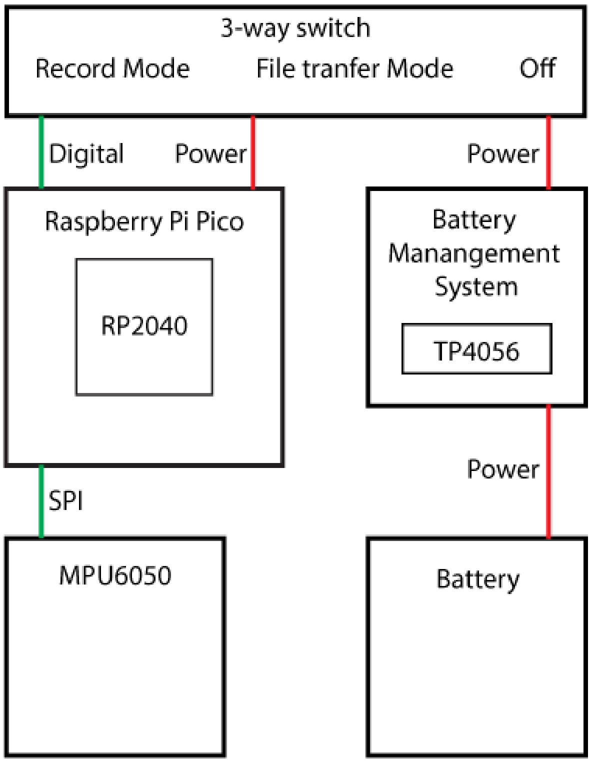


Figure 2.14: An overview of the electronics setup

also looks like the first lane is swam slower than the consecutive ones. When testing a new prototype note should be taken of the orientation of the sensor with respect to the wearer and the actions of the swimmer should be taken note of to accurately link the sensor data with the taken action.

2.8 Context Analysis Conclusions

2.8.1 Context Analysis questions

From the literature the report questions are partly answered. This section summarizes the findings first with a list and than with a paragraph going into more detail.
What has been answered:

1. What is the correct swimming technique of the front crawl and backstroke?
   - What the best practices for swimming technique are for swimming well.
   - What the most common problems are and which could use technical support.
2. How can this technique be measured?
   - What the different sensors that are in literature used for measuring swimming performance.
   - What some general signal processing techniques are that can be used for detecting a large variation of variables.
3. How can these measurements be used in combination with haptic feedback to facilitate motor leaning of the correct technique?

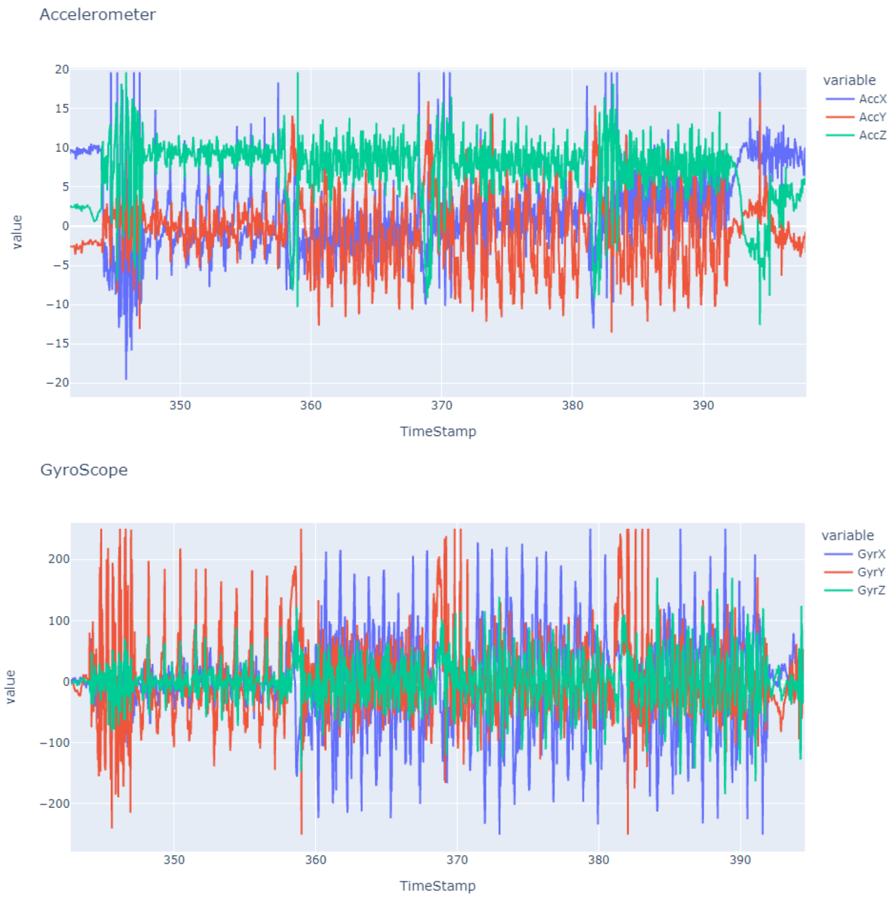


Figure 2.15: Sensor data of four lanes of swimming.

- What some techniques and mechanisms are that facilitate and some that hinder motor learning.
- What constitutes as good feedback for motor learning.

4. How can a wearable for an aquatic swimming environment be designed?
    - What the requirements are for a direct haptic feedback wearable for swimming.
5. What are the the other systems that make use of concurrent feedback during swimming?
    - What methods do they use to give concurrent feedback?
    - What are the strong and weak points of these systems?
    - What research would add meaningful value to this research space?

What is the correct swimming technique of the front crawl and backstroke?

Swimming comes down to a careful repetition of precise movements where arms, legs and torso work together to achieve the most efficient forward propulsion. The movement of the arms, where the hands push the water backwards, seem to be most responsible for providing the propulsion. During these movements the drag that is experienced due to the water is ideally minimised as much as possible. One method is to have the frontal area of the swimmer in the water as small as possible. The front crawl can be broken up in four arm stroke phases; the entry and catch, the insweep, the upsweep, and the recovery (see figure 2.1). In which the insweep and upsweep give actual propulsion to the swimmer. The IdC in this case gives a good indication of performance since it is an index of time spend in propulsion between the arms. A common mistake when it comes to fast and efficient swimming is that some swimmers do not have a continuous velocity. This can often be explained by a negative IdC. The kicking does not seem to be very important to actual propulsion. However, the kicking is an important movement to keep the body high to the water surface, reducing overall drag. Not laying high in the water is also one of the common mistakes [24] when it comes to fast and efficient swimming.

How can this technique be measured?

Swimming technique has been measured in many different ways: with the use of analysing video, prussure sensors, GPS and most notably using an IMU. Common measured variables are: stroke count and stroke rate, stroke identification, velocity, lap count and lap time. Most of these are not directly indicative of swimming technique, however, the way that these measurements are obtained can inspire methods from the next variable. Some of the methods used to measure these variables are computationally simple enough to be able to perform an analyses in real time like: zero crossing, peak detection and thresholding. However, some more computationally advanced algorithms are also used: frequency analysis, movement modeling. These are not suited for real time application. For measuring the body balance in real time it might be possible to use and IMU and a combination of the derivative of the angular velocity and the acceleration downwards due to gravity to get an estimation of the angle of the device and thus how much the swimming is laying flat in the water. The consistency of the swimmers speed might be able to be obtained by taking the derivative of the forward acceleration. These calculation should be doable in real time on an integrated device.

How can these measurements be used in combination with haptic feedback to facilitate motor leaning of the correct technique?

Swimming can be considered a complex task. Generally complex tasks benifit from more frequent feedback. There are however reasons to lower the amount of feedback given. One of the reasons is because of the guidance hypothesis, where the person practicing the task is getting used to the feedback in such extend that (s)he is not able to do the task anymore with the use of this feedback. Another reason might be to give more room for the person doing the task to more intently focus on their own motions rather than relying solely on external feedback for practicing.

For good feedback, it is also important to have the correct content of feedback as well as timing of when the feedback is given. As discussed in section 2.4, feedback should be: Accurate and relevant, appropriately timed and delivered, and decipherable by the athlete. That means that a variable should be chosen that is key for performance, accurately measurable and adaptable by the athlete. For haptic feedback, the feedback should be given as the mistake is made and a good metaphor should be designed for delivering this feedback.

How can a wearable for an aquatic swimming environment be designed?

The requirements wheel is a good tool to help setup requirements for any wearable. With an aquatic environment there are some things that become more important and some things that become less important. For instance, having the device to be water tight is essential for safety and durability reasons. Weight becomes less of an issue since it is easily offset with buoyancy. Hydrodynamics are important if the wearable needs to move through the water at any significant pace. Placement on the body can be done on the trunk, head, arms or legs and has mostly to do with what needs to be measured and if it interferes with normal swimming movements.

What are the the other systems that make use of concurrent feedback during swimming?

Previous research has examined five methods for providing concurrent feedback during swimming, utilizing both auditory [5, 6, 72] and visual [8, 9] methods. However, these implementations often rely on electronic devices mounted on the head [5, 6, 8, 72] or special environments [9], limiting their convenience for consumer use. Haptics offers a wider range of options for providing feedback on the body without the need for wires or experimental wireless technology [8]. This study will aim to fill this gap in research by exploring the use of haptic feedback in swimming.

2.8.2 Discussion

In section 2.4, several criteria were mentioned for effective feedback for motor learning. The feedback should be: i) Accurate and relevant, ii) appropriately timed and delivered, and iii) decipherable by the athlete. To meet the first criterion, knowledge needs to be acquired about the discipline in question and the measuring methods for that discipline. In section 2.1 common mistakes were discussed. Looking at the mistakes most detrimental to performance: 'Bad' body balance, and large variations in velocity [24]. These were also in the top 2 of things the coaches would like technological help for. Only then in opposite order. From this, one can conclude that large variations in velocity and 'bad' body balance would be good variables to focus on. This should be measurable from the back assuming that the the angle along the bilateral axis of the body is correlated with the angle of the back.

2.8.3 Reevaluate questions for further research

During this context analysis it became clear that the body balance can be used to give feedback on with a wearable device. The next step will be to develop a prototype and test the principle of giving feedback in a swimming environment on body balance. To do this the following research question and accompanying sub questions are defined:

RQ: How can a wearable device be designed to improve body balance in swimming with the use of haptic feedback?

- SQ1: How can a wearable be made water resistant and provide haptic feedback?
- SQ2: How can a wearable be designed for multiple body types and as a platform to explore haptic metaphors?
- SQ3: How can body balance be measured using a wearable device?
- SQ4: How can haptic feedback be made perceivable in an aquatic swimming environment?
- SQ5: What kind of haptic metaphor can be used for providing feedback on the body balance?
- SQ6: How can the system be evaluated?
- SQ7: How does the system compare to the state of the art?

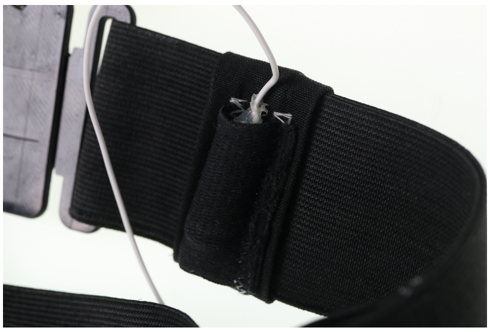
3 DEVELOPING A PROTOTYPE

In this chapter sub questions 1 and 2 will be answered:
SQ1: How can a wearable be made water resistant and provide haptic feedback?
SQ2: How can a wearable be designed for multiple body types and as a platform to explore haptic metaphors?
This chapter provides an overview on the hardware choices that have been made that helped shape the functionality and form of the eventual prototype.

3.1 Sealing against water ingress

The first test of sealing electronics was performed in section 2.7. For that prototype a 1.5 millimeter silicone lining was used in a 3D-printed case. In [2] a table is presented with different methods of sealing used in literature about measuring swimming with inertial measurement units. Many of these methods just describe a waterproof casing of some sort, or a certain brand name solution. It does not seem like there is a standard method of sealing electronics for use in swimming.
For making this hardware prototype a decision was made for using FDM 3D printing for making a casing to hold the electronics. This was chosen for the flexibility it provides in the final shape, as well as being quickly iterable. This makes it possible to quickly design a casing that meets the design requirements. There are methods of improving the chance of making water resistant FDM 3D prints. Acetone vapour smoothing is a technique to chemically melt the layers of an ABS 3D print together resulting in a smooth surface. This method of waterproofing was tried and rejected due to deformations during the process which caused the parts to come out dimensionally inaccurate. Instead, the choice was made to use a poured silicone liner. This was made in a separate mold and put into the casing. For the wires that needed to pass through the casing a method was used of first stripping partly the cables and than encasing the stripped

(a) Sealed vibration motors in a 3D print and epoxy glue.



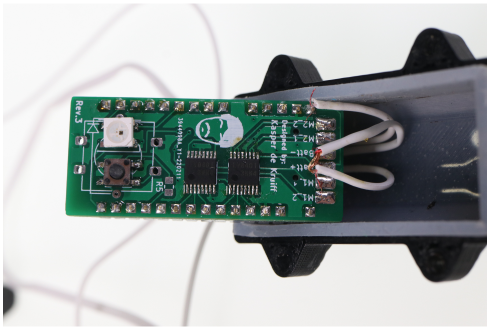
(b) The pocket in the harness for the vibration motors.

Figure 3.1: Vibration motors used for the prototype.

parts with two component epoxy glue trough an opening in the casing[1].
The wires were partly strain relieved by using silicone caulking around the bending locations. The silicone caulking was also important to glue the wires to the inner silicone liner. To make the seal sufficiently watertight and also maintain access to the electronics, the casing was bolted to a plate with a rectangular piece of silicone on it, so that the silicone liner was pressed against the silicone piece on the plate. The bolts are placed in such a way that they should provide fairly equal pressure along the liner to minimise the chance of any part breaking the silicone-silicone contact.
For the battery case the process is a little different. Instead of a silicone liner the inside of the casing was coated in a two part epoxy glue and a lid was made with a silicone piece that sealed against the epoxy coated plastic. The battery casing was made with clips all around the perimeter to have pressure all around the seal and also be able to open it quickly and toolless. This was important since the wearable turns on by supplying it with power and only turns off by removing it.

3.2 Electronics

For the electronics several things were important: there needs to be a micro controller with sufficient calculation power to do some on board signal processing, there needs to be two haptic motors that are sufficiently powerful and can be placed on several places on the body, it needs to have an interface that enables changing modes on the device, and it needs to be able to log sensor data.



(a) Front side, the two IC's are the motor drivers, there is a button and an LED on there.

(b) Back side, this side has the SD-card reader as well as the header pins to connect the shield to the Arduino.

Figure 3.2: Custom breakout board for additional electronics.

For this, an Arduino Nano RP2040 connect micro-controller board was used. This board contains the RP2040 micro-controller from the Raspberry Pi Foundation which is very suitable for wearable devices due to its low power requirements while still being able to perform quick calculations and it being quite small. The board also contains a ST LSM6DSOX 6-axis IMU. This chip is contains a gyroscope and accelerometer for precise movement tracking. Extra electronics were added with the help of a custom breakout board (an easily connected daughter PCB). This breakout board contains two LV8401V Motor drivers for driving the haptic motors, a momentary push button to be able to interact with the device, a WS2812B addressable RGB LED to indicate the status of the device (figure 3.2a), a SD-card reader for logging sensor data (figure 3.2b) and connectors for a battery pack. The battery pack that was made uses 3 rechargeable Ni-MH AAA batteries for a combination of small size, capacity and safety.

[1] http://www.homebuiltrovs.com/howtosealingwireexits.html

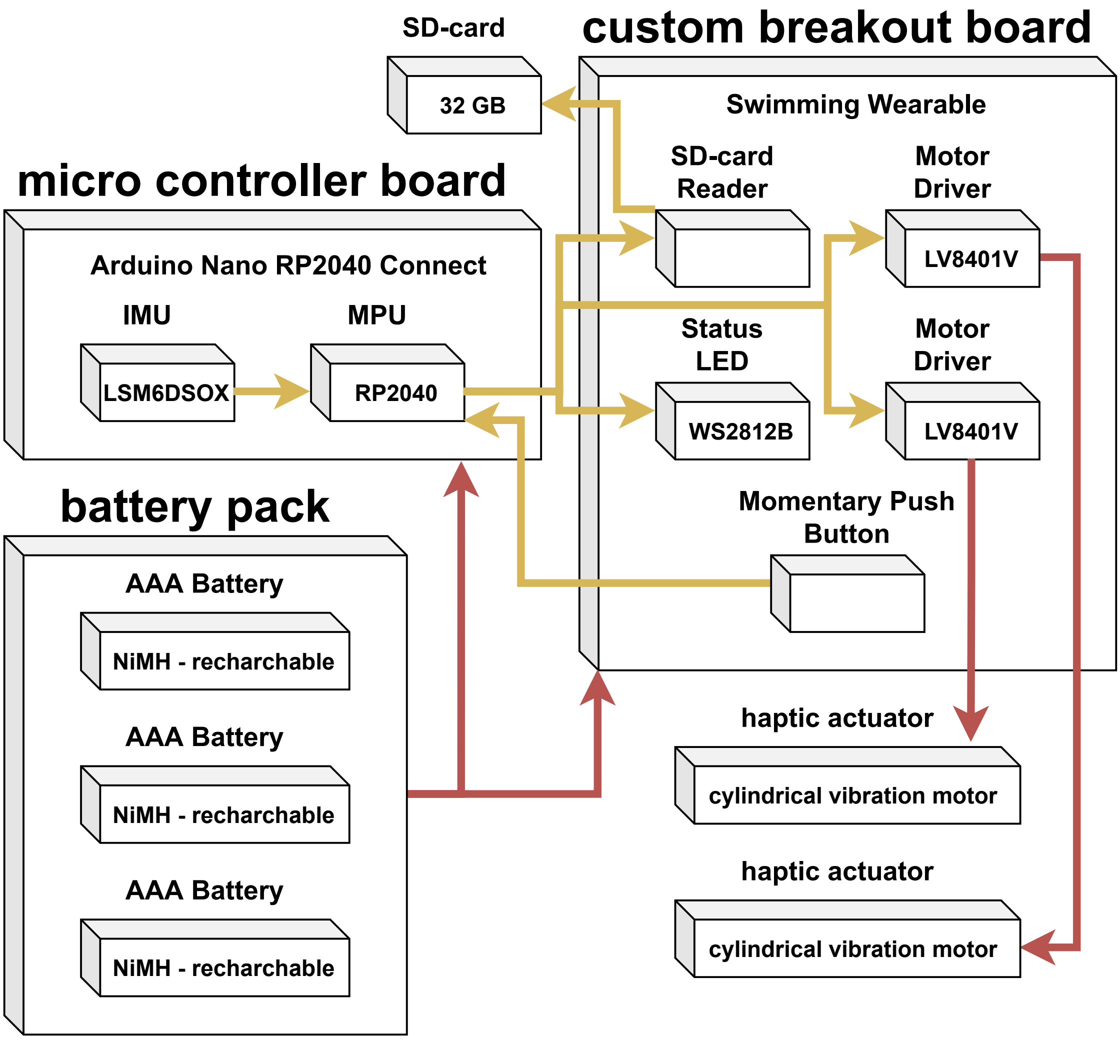
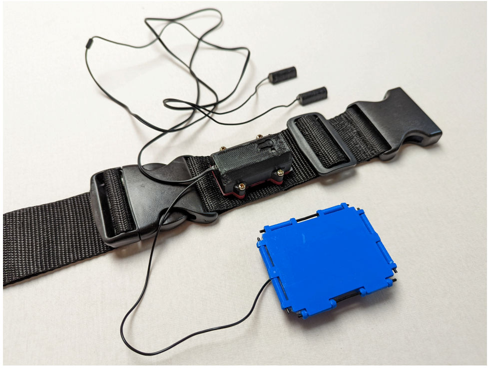


Figure 3.3: Schematic block diagram of the electronics used for the final prototype. The yellow lines indicate the main flow of a digital data signal and the orange lines the flow of analogue electric current.

3.3 Harness

firstly, the electronics were attached on the body by the use of an adjustable belt with non-elastic straps (see figure 3.4a). However, during swimming the belt would come loose or restricted movement if secured too tightly. Also, the belt would catch water and open up like an umbrella. To prevent this, a harness was developed that made use of elastic straps and was secured over the shoulders (figure 3.4b). Not only did this secure the location of the electronics better to a singular spot, it also shifted this location higher up the back. This allowed the wearable to measure the body angle also if someone tilts their hips backwards. The location will also be experiencing a larger body roll however. The harness was made to be adjustable and was fit-tested on very different body types to assures that it fits.



(a) The hardware was first on a belt that was worn around the waist.

(b) The final iteration of the prototype used straps to secure the hardware on the back.

Figure 3.4: Vibration motors used for the prototype.

3.4 Functionality

The firmware on the device has different modes that are navigated using the push button on the device. The full Arduino code can be found in appendix B. Different combinations of short, long, double and triple press are used for this. The indicator LED shows in which mode the device is or what it is doing based on different colours and fade patterns. The different modes are: Recording mode, in this mode all the sensor data is logged to the SD card; Calibration mode front crawl, as soon as the swimmer starts laying prone the wearable records five seconds of swimming to determine the threshold value for when the feedback will be given for front crawl swimming; Calibration mode backstroke, this is similar to the previous mode but then for the backstroke; Feedback mode front crawl, in this mode feedback will be administered as soon as the the body angle falls below the previously determined threshold value; Feedback mode backstroke, similar to the previous feedback mode but for backstroke. For the Feedback during the front crawl the first 3 degrees the haptic feedback will increase in strength linearly. After that the vibrations are at maximum strength until the pitch is greater than 50 degrees. The assumption is that the swimmer will then be standing or hanging at the sides and not swimming. For the backstroke it works similarly but the window for linear increase of vibration strength is 10 degrees. This is because the variation between a good and bad body angle is greater.

3.5 Conclusions

Using a combination of silicone, epoxy, screws and 3D-printing a wearable was made capable of leaving the internal electronics dry during swimming. This gives an answer to subquestion 1:
SQ1: How can a wearable be made water resistant and provide haptic feedback?
By making a harness that is adjustable and makes use of elastics several body types can be accounted for. Also, by having two haptic motors on a wire the haptic feedback can be given on multiple locations. This answers sub question 2:
SQ2: How can a wearable be designed for multiple body types and as a platform to explore haptic metaphors?

4 BODY ANGLE CALCULATION

In this chapter, sub question 3 will be answered:
SQ3: How can body balance be measured using a wearable device?
A method for angle calculation is posed. For testing the accuracy of the angle calculation a benchmark test is performed. This should highlight any overshoots and damping effects to be able to validate the eventual results. Next to this a field-test is performed in which the researcher swims with different body angles while the wearable calculates the angle. This test will confirm the possibility to differentiate between body angles.

4.1 Angle Calculation

For determining the body balance angle the direction of gravity is used as a reference. The IMU on the Arduino I use contains a gyroscope and an accelerometer. The gyroscope measures angular velocity around three perpendicular axis and the accelerometer measures linear acceleration along these same three axis. For determining the angle around the x-axis the angular velocity times the sample rate is added to the previously calculated pitch. To mitigate the drift that occurs from summing errors, the accelerometer is used to reference the pitch angle to the gravity. ξ is used as a ratio term from 0 to 1. The higher this term the more the gyroscope pitch is used to calculate the angle. $\xi = 0.999$ is chosen for the implementation of this calculation of the angle.

$$\theta_{GyrPitch} = \theta_{CurrentPitch} + \omega_x * \Delta_t$$

$$\theta_{AccPitch} = arctan(a_y / \sqrt{a_z^2 + a_x^2})$$

$$\theta_{NewPitch} = \theta_{AccPitch} * \xi + \theta_{GyrPitch} * (1 - \xi)$$

4.2 Setup Benchmark Test

To test the accuracy of the angle calculation a benchmark test was performed. For the setup of this test a little seesaw which houses the sensor has been made. This seesaw has two end-stop positions between which the angle of the sensor can change. This can be seen in figure 4.1. A recording will be made of the angle while the seesaw is moving from one end-stop to the other. First, a static measurement will be taken while the seesaw is at its far right, far left position, and while being level. A bubble level app on a phone will be used as a reference measurement. Secondly, the seesaw will be set from one point to the other at different speeds. First over approximately 5 seconds, then 2 seconds, then as quick as possible. These recording can then be analysed and the features highlighted in plots.

(a) Setup tilted to the far right. Using phone app for angle reference, value on screen shows 20.16°.

(b) Setup tilted to the far left. Using phone app for angle reference, value on screen shows 15.13°.

Figure 4.1: Test setup consisting of a seesaw that moves freely between two points. The hardware is mounted on the left side of the plank.

4.3 Results Benchmark Test

In figure 4.2 three angles are tested. The first third of the graph shows what the wearable calculated when left level (0°), the second third when held all the way to the left (15.13°), and the last third when held to the right (-20.16°). The wearable showed an offset for each of these conditions. This offset was constant at -1.9° and likely due to the electronics being a little slanted inside of the case. In figures 4.3, 4.4 and 4.5 a dynamic test was performed. The results of the

Figure 4.2: This is a measurement where the wearable is first held level, then at 15.16°, then at -20.16°. The wearable measured these values respectively: -1.93°, 13.27°, and -22.02°.

benchmark showed that when the angle of the seesaw changed, the gyroscope action got the calculated angle quickly close to the expected value, however not completely. This can either be due to a mismatch in sample time, or a factorial error. The accelerometer corrected this, however it took several seconds. using the gyroscopes angular speed, it can be inferred when the seesaw was done turning. At this point the calculated angle is denoted with a red dot in the plots. When slowly changing the angle the difference between the eventual angle was only 0.6° and 0.8° (see figure 4.3). It did take 2.4s and 2.7s to get to the eventual angle. When the seesaw was moved more quickly the difference also increased. In figure 4.4 the differences are 1.8° and 1.6°, and in figure 4.5 the differences are 8.2° and 18.4° respectively. The time to reach the eventual value also increases to almost 5.5s.

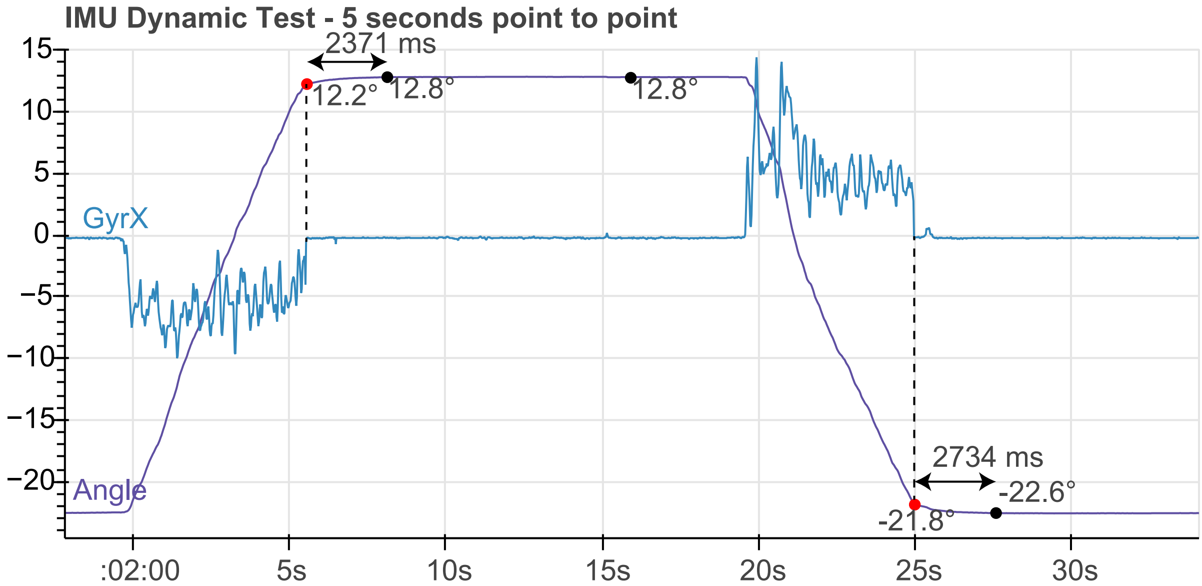


Figure 4.3: Here a recording was made of tipping the seesaw setup from one point to the other in approximately 5 seconds. The blue line is the angular velocity around the X axis of the gyroscope, the purple line is the calculated angle of the wearable. The x-axis of the graph is time in s and the y-axis is the calculated angle in degrees.

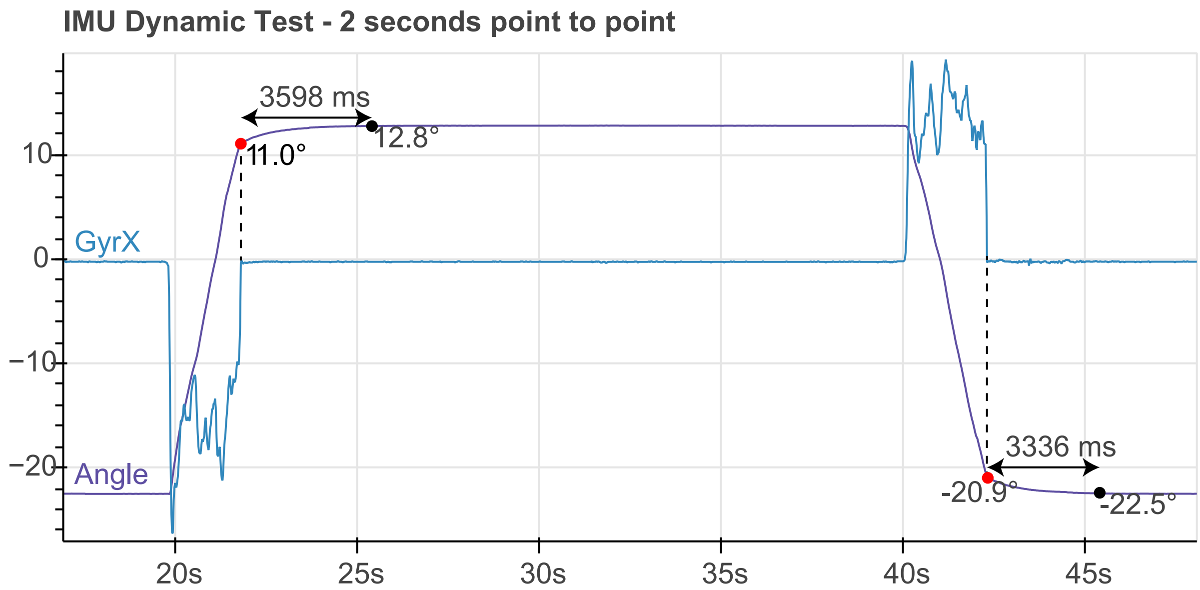


Figure 4.4: Here a recording was made of tipping the seesaw setup from one point to the other in approximately 2 seconds. The blue line is the angular velocity around the X axis of the gyroscope, the purple line is the calculated angle of the wearable. The x-axis of the graph is time in s and the y-axis is the calculated angle in degrees.

4.4 Setup Body Angle Differentiation

To be able to give proper feedback on body balance, the wearable needs to be able to differentiate between different body angles. To see if this is possible a test is setup. The wearable will be worn around the waist and during swimming the researcher will swim alternately with very large body angle (angled with legs lower), how he swims normally, and with a very small body angle (body parallel to the water surface). Figure 4.6 shows what these angles look like during swimming. During this swim session a recording of the body angle will be made and evaluated.

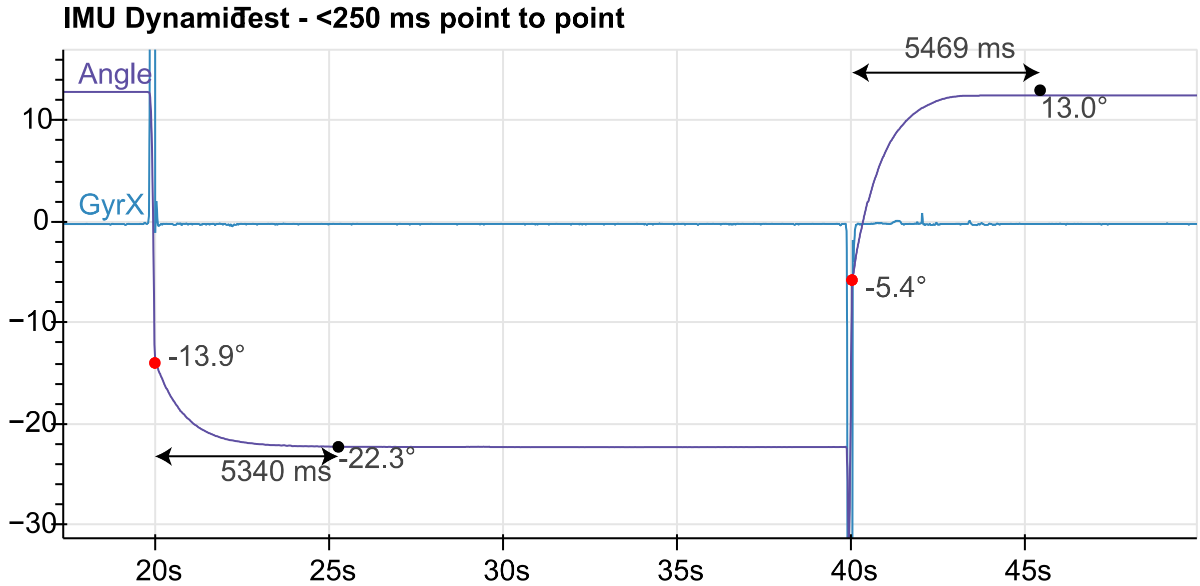


Figure 4.5: Here a recording was made of tipping the seesaw setup from one point to the other in less then 250ms. The blue line is the angular velocity around the X axis of the gyroscope, the purple line is the calculated angle of the wearable. The x-axis of the graph is time in s and the y-axis is the calculated angle in degrees.

4.5 Results Body Angle Differentiation

Figure 4.7 depicts the calculated body angle over time for 12 lanes of swimming. The red line shows a walking average filter over the data and the blue line shows the calculated body angle over time. Every time a big deflection can be seen in the blue line a new lane is started. In the figure a stair-step effect can be seen every three lanes, since the swimmer changed their body angle every lane.

4.6 Conclusions

From the benchmark test and the differentiation test it became apparent that an angle can be determined using an IMU. However, there are limitations to the angle calculation method. Firstly, there is a offset from the real angle. This shouldn't matter though, because only the relative change in angle is important for this study. Secondly, The angle calculation starts out undershooting from the eventual value and needs some time to come to this value. Despite these limitations however, the obtained data is likely still valid to be used for estimating a body angle as can be seen in the differentiation test in figure 4.7. The rate of change in angle during the swimming seems not great enough to significantly inhibit the ability to determine a usable value for the body angle.
The method proposed in this chapter for calculating the body angle thus gives an answer to sub question 3.
SQ3: How can body balance be measured using a wearable device?

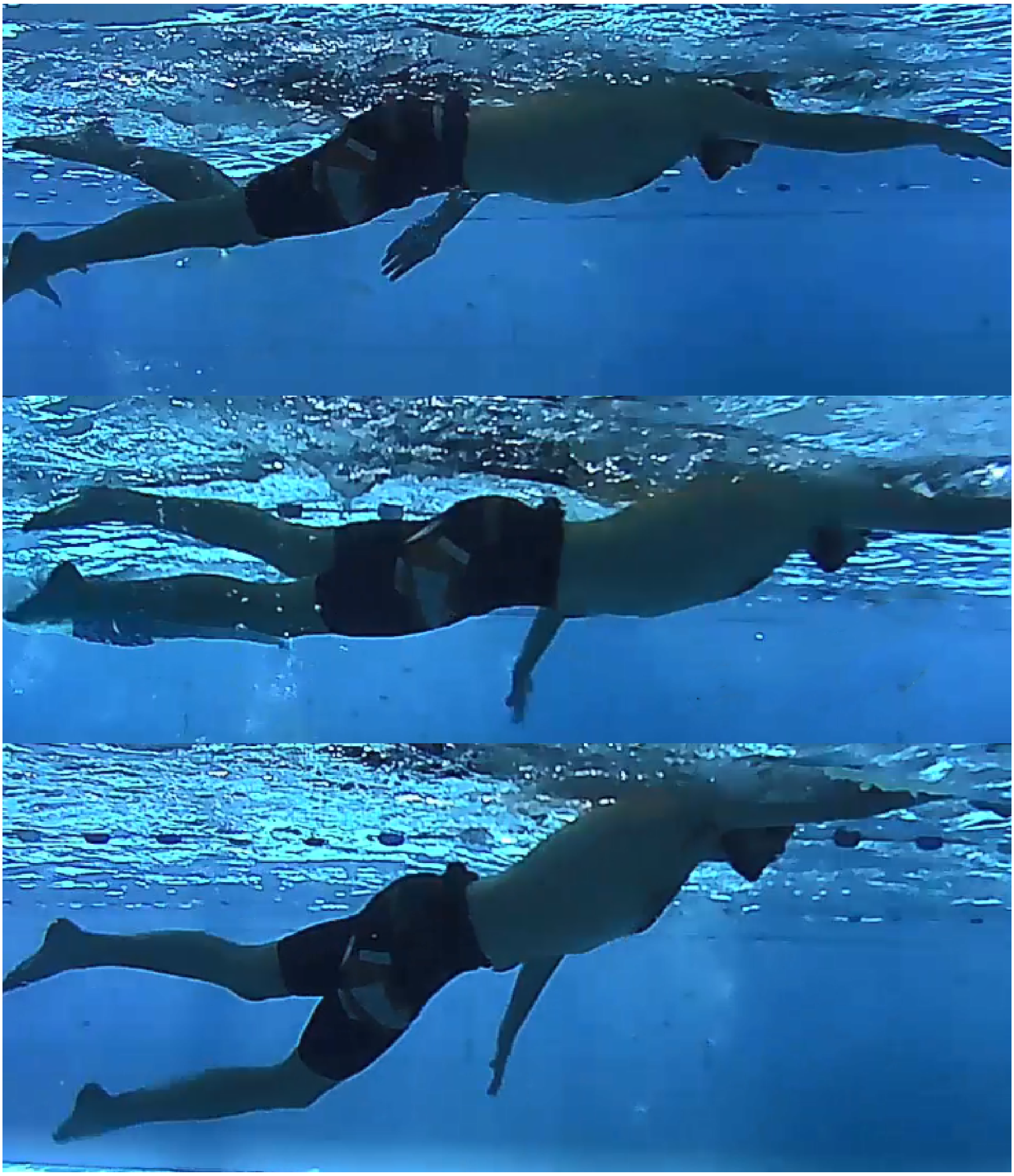


Figure 4.6: The photo's depict the different body balances during swimming. Top photo: high body balance. Middle photo: medium body balance. Bottom photo: low body balance.

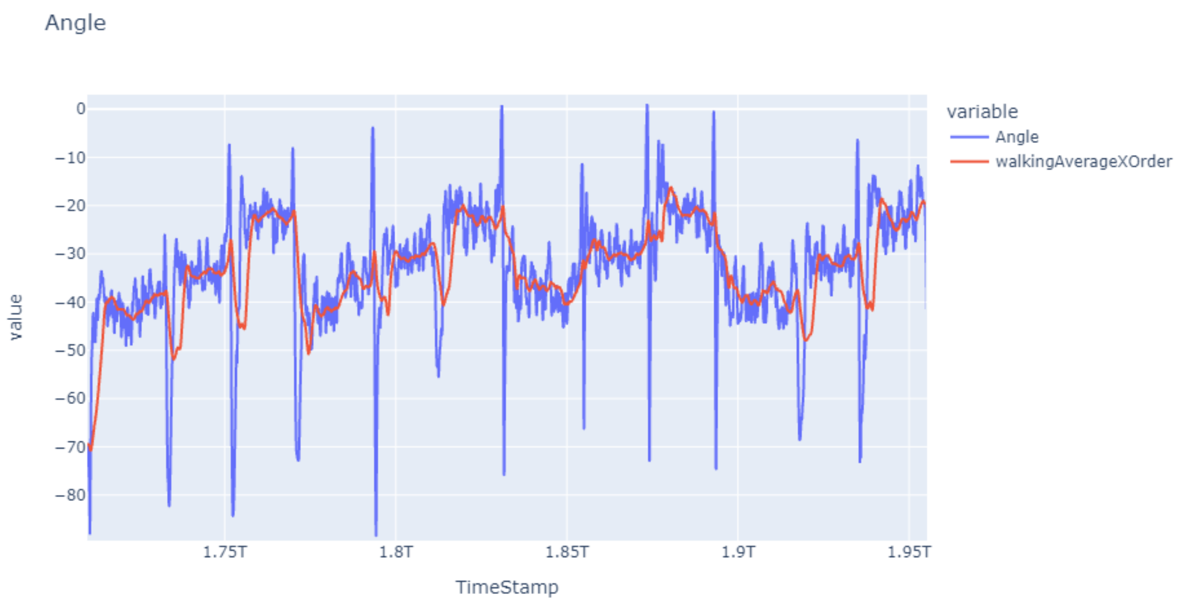


Figure 4.7: This figure shows a swimming bout of 12 laps (pool-length of 16.66m). Each lap alternates between swimming with a low body balance, a medium body balance, and a high body balance. The filtered signal line is a moving average filter over 200 samples at 50Hz.

5 VIABILITY OF HAPTIC FEEDBACK

In this chapter sub question 4 is answered:
SQ4: How can haptic feedback be made perceivable in an aquatic swimming environment?
To answer this question a test is done in which the researcher places the haptic motors at several places on the body using a body safe tape and rates the perceivability of the haptic feedback.

5.1 Setup Perceivability Test

To test the perceivability the haptic motors are set to vibrate in an on-off pattern with a frequency of 1 Hz. The motors are place on different parts of the body and a few lanes are swam. A grade will be given on how noticeable the vibration is for every location along with comments if necessary.

5.2 Results Perceivability Test

There seemed to be a difference in the perceivability of vibratory haptic feedback on various places on the body during swimming. The subjective perceivability for different body locations has been reported in table 5.1.

#	Body Location	Remark	Perceivability score 1 - 10
1	Shoulder blade	Difficult to feel when swimming fast.	3
3	Middle of spine	Better than #4.	5
4	Lower back	Meh. Difficult to feel when swimming fast.	3
5	Back of the neck	Difficult to feel when swimming fast.	3
6	On the hip	Not very noticeable, seems to disappear with the turn.	4
7	Back of the upper leg	Perceptible, not great.	4
8	On the nipple	Could not test due to too much hair.	-
9	On the breastplate	Perceptible.	5
10	Above the navel	Perceptible.	6
11	Under the navel	-	5
12	On the quadriceps	Oké during free swimming.	5
13	Side of upper leg	Perceptible during faster swimming.	5
14	Inner thigh	Loses perceptibility with stronger leg movement.	6
15	On the glute	Pretty perceivable, also with stronger swimming.	7
16	Side of the neck	Very present, also audible.	8
17	Just under the ribs	Sensitive, very clear.	8

Table 5.1: This table shows the observations made during testing of the perceivability of the haptic feedback on different body locations. These are highly subjective and primarily to develop a grasp for the possible body locations suited for haptic feedback during swimming.

5.3 Conclusions Perceivability Test

On certain locations the vibration seemed more noticeable on than others. It is difficult to determine how noticeable the feedback would be if the focus was not specifically on the feedback. Generally, If a lot of water passes a certain area the vibration from the haptic engine becomes less noticeable. It felt as if just below the ribs is a relatively sensitive part while still being easy to access. This is done with only one person and is done only once so no hard conclusions can be drawn from this experiment. With that a preliminary answer is given to sub question 4:
SQ4: How can haptic feedback be made perceivable in an aquatic swimming environment?

6 VIBRATION METAPHORS EXPLORATION

In this chapter sub question 5 is answered:
SQ5: What kind of haptic metaphor can be used for providing feedback on the body balance?
For exploring a suitable way of implementing the wearable technology that has been developed, user tests can be conducted. For this experiment, participants tried several different methods of feedback and they were asked questions about it. Before performing the experiment, the ethical committee of the University of Twente had approved this test methodology[1].

6.1 Finding a Suitable Haptic Metaphor

For determining a haptic metaphor that is intuitive for most people the different options need to be considered. Three things are important when determining the right metaphor: placement, intensity and patterning. To limit the scope of the research and make the technical implementation more feasible a maximum of two vibration motors are used.

6.1.1 Intensity and Pattering

Only one feature needs to be conveyed to the user; the body angle. This can be done in a continues, discrete or binary fashion. The vibration patterns can be changed in intensity, frequency and length of on-time, or any combination of these three. Each motor can be doing the same action or the opposite action. Also, the action can be positively of negatively correlated to angle of the body, indicating a need to move towards the location of the haptic vibrations, or away from it (pushing or pulling). It will not be possible to test all of these different combinations. To still come to a conclusion to which combination of these features works well, the plan is to handle the problem, not with a large amount of A-B testing, but by first making assumptions by designing a few different haptic displays, and test those few options. By leaving the conversation open and asking for preferences from the participants some new insights might be obtained.
A choice was made to only have give haptic feedback if there is something to improve. Because haptic vibrations demands some attention from the user. This attention might be distracting when swimming correctly and necessary for receiving feedback.
From here, three different haptic patterns were designed for testing. From the previous test about the perceivability during swimming it became clear that very low intensity vibrations are difficult to feel. The simplest form of feedback is on and off, where the motors vibrate at maximum intensity whenever the body angle passes a certain threshold. This form of haptics is called the blue mode for the rest of the experiment.
Another method of keeping the intensity high, while also giving more information about the size of the body angle, is by changing the patterning by modulating the frequency and on-time. For the green mode the frequency as well as the on-time of the vibration would increase when the body angle got bigger; worse body balance. At some larger angle the vibration will be statically on.
The yellow mode made use of a modulation in intensity. In this mode the first few degrees of

[1] Request nr.: RP 2021-230

the body angle below a threshold were modulated linearly from off to weak to strong to fully on. After that the wearable would be fully on.

6.1.2 Placement

Anywhere on the skin can be used for giving haptic feedback. Some places are more suited than others, for this we need to consider the following:

- The location of stimulation should be socially acceptable.
- The location of stimulation should not interfere with the activity of swimming.
- The location of stimulation should be such that it can still be felt under water during swimming.
- The location of stimulation should ideally give an intuitive hint on the desired outcome.

For securing the first requirement we can simply rule out obvious erogenous locations such as the breasts, anus and genitals. Some might consider on the glutes and near the groin to be off limits as well. The face is also considered quite personal since the need to communicate. Three locations were chosen to suggest to the participant to try:

- On the hips at the front. This makes for a clear push metaphor, since this needs to go up to correct the body balance and is close to the legs and core which are both responsible for correcting body balance.
- Underneath the belt of the harness at the ribs. From the perceivability experiment this was a standout, for it was relatively perceivable compared to other locations.
- Underneath the belt of the harness at the back. This location is chosen as a pull metaphor while not placing the haptic actuators on the glutes, which is likely to be perceived as inappropriate. Placing the actuators underneath the belt also gives some pressure which might help the vibrations to be more noticeable.

6.2 Setup

In this paragraph the the setup of the experiment that will answer sub question 5 will be laid out. The experiment consists of a section before the actual experiment during which the consent form is filled in and explanations of the experiment are given. Thereafter, the participant will put on the wearable and a calibration will be done in the water before starting with a small amount of swimming. After swimming and experiencing the feedback there is room for the participant to comment on the experience. Another location for feedback is tried several times before finally asking the participants a few more general questions after which the experiment is ended.

Before experiment:

- The participant is asked to fill out a consent form.
- The researcher explains the goal of the research and the general working of the device:
    1. During swimming it is important to have the right swimming form. Laying too low in the water can result in too much drag.
    2. This device contains a sensor to measure its tilt, therefore being able to measure the tilt of the swimmer.
    3. The vibration motors can vibrate depending on the tilt of the swimmer.

4. Thus, can give feedback on the swimming technique of the swimmer.
5. You will be asked to swim sloppy as well as correctly to evaluate the feedback that you can get from the device.
6. The goal of this experiment is to find a suitable vibration pattern and location to give feedback.
7. For that there first will be a calibration and then different feedback patterns and placements will be tested.

- The participant will put on the wearable and the haptic motors are placed at the first feedback location.

Swim and feedback part:

1. In the pool, have the participants lay face down in the water while the wearable sets a threshold value.
2. The sound recording is started to safe the comments of the participant.
3. The participant is asked to swim two lanes.
4. After swimming ask short questions:
   - Do you need more swimming to evaluate?
   - Anything of note so far?
   - How easy or difficult would you say it was to feel the vibrations?
   - Did you feel like the feedback gave you indication on what to do?
5. Change feedback locations and feedback mode a few more times and let the participants swim again with the new combination of location and pattern. Whether backstroke or front crawl is swum will be determined in discussion with the participant.
   - On the hips, green mode
   - On the ribs, yellow mode
   - on the back, blue mode
6. Before ending the experiment, the participants are asked if they want to try one of the feedback modes on a different location.

Interview questions to end the experiment:

1. Can you describe which method of receiving feedback you liked or did not?
2. Is there a difference in importance of the two modalities of receiving feedback or are they the same? For instance: do you feel like the feedback pattern is as important as the feedback location?
3. Did you feel like the vibrations were in line with your swimming performance? Did you received vibrations when you needed to receive vibrations?
4. Do you feel this wearable could help you become a better swimmer?
5. BONUS: Is there something you would like feedback on? Any features that you would like the wearable to have? (more a question for fun)

The participants were also asked to swim several lanes with good and bad body balance that is then recorded. This recording has been used to validate feedback methods and data analysis methods.

6.3 Results

Three participants were included in this experiment. In appendix G the interviews and general happenings are minuted. Here are the main findings of those interviews:

- All participants reported that the vibrations were not very clear on the body. However, they were all able to feel the vibration and act upon haptic feedback.
- Interviewees all thought the most important quality of the body location was the ability to perceive the vibrations. The location did not seem to matter on how intuitive the feedback was. One participant even put the vibration motor underneath the elastic of their swimming goggles to, in addition of feeling the feedback, also hear the feedback.
- From the three participants, it seemed that different people prefer different locations for feedback. Participant 1 prefers underneath the elastic band on the front on the ribs. Participant 2 did not try that position but has tried on the back of the head which they prefer because of the easier perception. Participant 3 preferred the back of the torso more than the front of the torso, also due to perception reasons.
- Calibration was a bit of an issue. People doubted their swimming ability and it was difficult to come to a point where the wearable set a threshold that was neither too high or too low. Also, participant 3 seems to have more of a curve in their back which wasn't accounted for when designing a calibration sequence.
- Of the three modes that were presented, the mode that changed frequency and vibration time (green) was not intuitive for the participants. Participant 3 also notes that this mode seems slower and that knowledge on the distance from the threshold is not important to them.
- The binary mode (blue) and the mode that has a bit of a ramp (yellow) where both perceived as binary by participant 1 and 3. Participant 2 could tell the difference but that might be due to the fact that they could hear the motor. Before, when they put the vibration motor on the rump, they said that the small vibrations were barely noticeable.
- Although the blue and yellow mode were perceived as binary, the blue mode was perceived more sensitive (participant 1) or more annoying (participant 3).
- All participants felt the wearable was able to measure the tilt and give feedback on that.

6.4 Conclusions

From the interviews it became clear that the frequency and on-time modulation was not intuitive for participants. A simpler form of feedback might thus be a better solution. Only having a binary on-off action was preferred by some but the binary mode (blue) was also perceived as annoying while the yellow mode (ramps up based on the body angle) was perceived as binary. Location also did not seem to matter much for understanding the feedback.
The preference of location did come down to perceivability. There was no clear consensus on this however. One person preferred the back of the head to be able to hear the motor. For this thesis we are not testing auditory feedback though, so this finding will be disregarded.
Because of these findings and those from the perceivability test, the final implementation will make use of a change in intensity based on the body angle, and the placement of the actuators will be on the ribs underneath the belt of the wearable. With that, sub question 5 has been answered.
SQ5: What kind of haptic metaphor can be used for providing feedback on the body balance?

7 EVALUATION METHODOLOGY

In this chapter a method will be proposed to answer sub question 6:
SQ6: How can the system be evaluated?
A separate question will be posed that more clearly describes the system and what can be evaluated to answer this sub question. For the final experiment the test condition will be tested against the control condition. In this case, all the participants will swim three times: one time without feedback before they receive any feedback, the baseline phase, as a baseline test; one time with feedback, the feedback phase, as the test condition; and the last time without feedback again after the test condition, the retention phase, to see if they retained their body balance. The participants will also be asked to fill in a short survey about their awareness of their body balance every time they go into a new test phase. This will be done for the backstroke as well as the front crawl. Afterwards they will be asked a few questions about the feedback. Before performing the experiment, the ethical committee of the University of Twente had approved this test methodology[1].

7.1 Posing Evaluation Research Question

A separate, more focused, research question is used to evaluate the system and the underlying principles. This new question should contain what the exact principle is that is being tested and can be used as a mainstay for designing a suitable experiment:
"To what degree does concurrent haptic feedback, using a push metaphor, lead to an immediate and lasting change in body balance during front crawl and backstroke swimming practice using a wearable device."

7.2 Recruitment

For this experiment a convenient sample had been chosen. The local student swim association (S.Z.V. Piranha) and the local triathlon association (D.S.T.V. Aloha) are asked to inform their members about this experiment. The triathlon association also allowed for testing during their training. Besides these associations also word of mouth was used as well some participants who were interested in the test I was performing. The aim was to recruit 16 participants, in the end 19 were recruited of which one person performed the test a second time due to loss of video data and one person was not able to finish all components of the test. So in the end there is a sample size of n=18.

7.3 Collected Data

For the experiment the following data will be collected:

1. Per participant demographics: age, gender, years of sport related swimming experience, level of swimming.

[1]Request nr.: RP 2022-48

2. Per participant remarks and opinion on the wearable and the haptic feedback.
3. Per participant survey data to get a measure of awareness over their body position.
4. Per participant the body balance angle over time.
5. Per participant the calibration value at every point in time.
6. Underwater video data of the swim practice.

7.4 Body Awareness Measure

To get suitable questions for the body balance awareness survey, first a list of different questions was made. Sixteen students from the Interaction Technology Master program at the University of Twente were asked what the measure was that is measured with the questions and which questions best support this measure. From this, the following questions were chosen for a short survey:
During swimming:

1. I actively adjust my body balance often.
2. I notice when my body balance is flawed
3. I tend to forget my body posture
4. I am actively aware of the angle of my body

These questions used a Likert scale with the labels: Strongly Disagree, Disagree, Somewhat Disagree, Neutral, Somewhat Agree, Agree, and Strongly Agree. In appendix F the format of these questions can be found. The surveys were laminated and a whiteboard marker was used to answer the questions. The third question is a question which signifies a higher body balance awareness if it is answered less agreeably.

7.5 Interview Questions

The goal of the interview is to enrich the sensor collected data and gauge the sentiment of haptic feedback during swimming and the device specifically. The interview answers might explain the readings from the sensor. For instance, age might play a role in the stamina of a given participant, as well as swimming level.

1. How old are you?
2. What is your biological sex?
3. How long have you been practicing swimming as a sport?
4. How would you describe your level swimming? If possible, can you back this up with objective statements? (e.g.: time over 50, 100, 600m; attended swimming events; other involvements with swimming.)
5. Can you describe what of receiving feedback you liked or did not?
6. Was it clear or unclear what the feedback meant? Did you receive vibrations when you needed to receive vibrations?
7. Would you say the feedback had influence on the way you were swimming? Did it change over time?

8. Do you feel this wearable could help you become a better swimmer?
9. Any other things you noticed?

7.6 Experiment Sequence

The experiment is set up to measure a difference between swimming without feedback and with feedback. For that the experiment starts an explanation of the wearable and what the test is going to look like. It continues with a baseline test in which the participant is asked to swim like they normally do. Then there is a calibration phase in which a threshold value is determined based on a little stretch of swimming. The average of 10 seconds of free swimming (between the sides of the pool without underwater phase or turn) is recorded and the samples are averaged. A predetermined offset is taken from this value and the participant will experience feedback as soon as their body angle crosses this value. They are asked if the amount of feedback they receive is not too little or too much. This can be adjusted up and down if needed. They can try a few more lanes if they need to and the feedback threshold is set according to their feedback on it. After that they would continue to the feedback phase, in which they receive feedback based on their body balance and the feedback threshold. The test ends with a retention test, where they swim again without feedback, and a set of interview questions. Read below a detailed sequence:

1. Short explanation
2. Signing consent form
3. **Baseline phase**
   (a) 6 lanes of front crawl swimming
   (b) Body balance awareness survey
   (c) 6 lanes of backstroke swimming
   (d) Body balance awareness survey
4. *Threshold calibration*
   (a) A few lanes (1-4) of front crawl swimming for setting a threshold
   (b) A few lanes (1-4) of backstroke swimming for setting a threshold
5. **Feedback phase**
   (a) 6 lanes of front crawl swimming
   (b) Body balance awareness survey
   (c) 6 lanes of backstroke swimming
   (d) Body balance awareness survey
6. **Retention phase**
   (a) 6 lanes of front crawl swimming
   (b) Body balance awareness survey
   (c) 6 lanes of backstroke swimming
   (d) Body balance awareness survey
7. *interview*

7.7 Data Interpretation Methods

7.7.1 Annotation of the Sensor Data

From the experiment a recording of the sensor data is saved. This recording needs to be annotated so that only the free swimming phases are included in the evaluation of the wearable. In figure 7.1 an example is given of the data and how it is annotated. The turning points usually show up in the body angle data with big spikes. A few times this peak was not present because of a unique turning technique or the peak was difficult to distinct from the other peaks present. In this case, the raw accelerometer and gyroscope data would be used. This shows a periodic signal which is interrupted as soon as the swimmer starts and ends the turning phase. Video data was used to verify undefined anomalies in the data. For instance, a large dip in the middle of the lane can be caused by two swimmers running into each other.

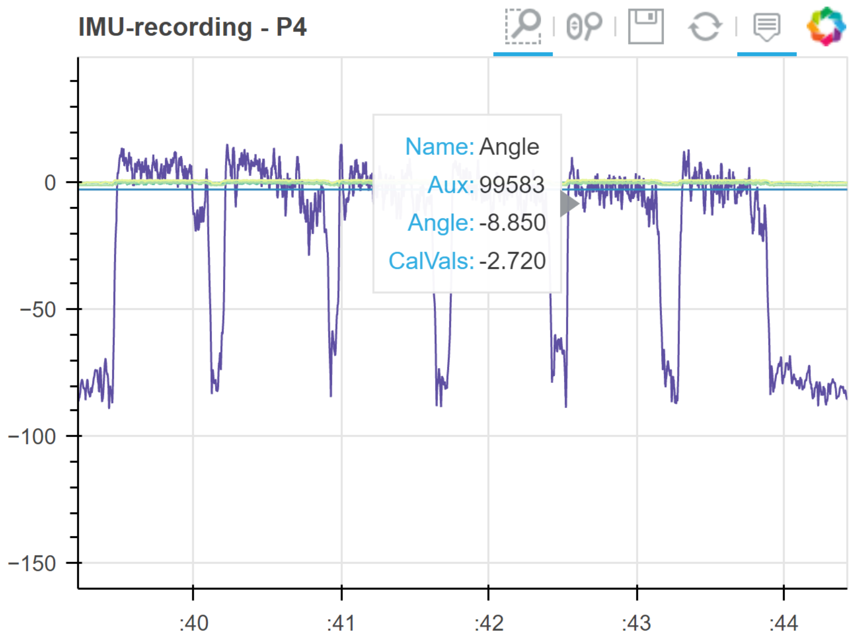


Figure 7.1: Making use of the Bokeh python library to plot the recorded body angle and identify the free swimming phases. A hover tool is used to find the beginning and end of each lane for each participant. This is a popup rectangle that shows up when hovering over the line graph. The Aux value in the hover tool denotes the index of the sample, which is used as a marker for further analysis.

7.7.2 Feature Extraction

For the interpretation of the sensor data two measures are defined: the Relative Average Body Angle, or RABA, and the Time Spend Under the Threshold, or TSUT. The RABA is a measure of the average body angle per test phase relative to all the test phases of a swimmer. The TSUT is a measure of how much feedback the participants would have received per lane, or did receive, if the haptic feedback was turned on.
To calculate the RABA first all the samples of a given test phase (Baseline or B, Feedback or F, and Retention or R) are added together. The separate lanes are annotated, so to do this the time stamps of every lane are called $\boldsymbol{S}_x^\tau$ of which x is the given lane and τ the test phase:

$$\boldsymbol{S}_x^\tau = \{t | t\, is\, every\, timestamp\, of\, the\, recorded\, samples\, in\, testphase\, \tau\, lane\, x\}$$

To get all the samples of a given lane in a given test phase, the set $\boldsymbol{T}_x^\tau$ is defined as follows:

$$\boldsymbol{T}_x^\tau = \{s(t)|s(t)\, is\, a\, sample\, taken\, at\, time\, t,\ t \in \boldsymbol{S}_x^\tau\}$$

All the samples of all the lanes l are then merged to make a combined $\boldsymbol{T}^\tau$:

$$\boldsymbol{T}^\tau = (\boldsymbol{T}_1^\tau, \boldsymbol{T}_2^\tau, ..., \boldsymbol{T}_l^\tau)$$

A combination of all the sets of the test phases, with $B : baslinephase$, $F : Feedbackphase$, and $R : retentionphase$ can be defined as follows:

$$\boldsymbol{T}^{total} = (\boldsymbol{T}^B, \boldsymbol{T}^F, \boldsymbol{T}^R)$$

To calculate the RABA of a given test phase τ, the mean of $\boldsymbol{T}^\tau$ is subtracted from the mean of the $\boldsymbol{T}^\tau$ of all test phases. $|\boldsymbol{T}^\tau|$ denotes the cardinality of $\boldsymbol{T}^\tau$:

$$RABA^\tau = \sum_{s \in \boldsymbol{T}^\tau} \frac{s}{|\boldsymbol{T}^\tau|} - \sum_{s \in \boldsymbol{T}^{total}} \frac{s}{|\boldsymbol{T}^{total}|}$$

The TSUT of a test phase is obtained by taking all samples of $\boldsymbol{T}^\tau$ that are smaller than the feedback threshold value $v_{threshold}$ of the participant, multiplying the amount of those samples by the sample frequency f_s and dividing that by the number of lanes swum l in that test phase:

$$\boldsymbol{U}^\tau = \{x | x \leq v_{threshold}, x \in \boldsymbol{T}^\tau\}$$

$$TSUT^\tau = \frac{|\boldsymbol{U}^\tau| * f_s}{l}$$

7.7.3 Variable Analysis

RABA and TSUT

For every participant a RABA and TSUT is determined. Then, a repeated measures ANOVA test will be used together with a post hoc paired wise t-test with a Bonferroni correction to determine if there are significant differences between the baseline phase, the feedback phase, and the retention phase for both the front crawl and the backstroke.

Body Awareness

For the body awareness survey the answers of the third question will be re-coded so that the alignment of all the questions is the same (answered more agreeable stands for a higher body balance awareness). These results are plotted on a stacked bar graph and sorted to tell which questions, during which stroke and test phase, were answered most agreeable.

Interview

The demographics that are asked during the interview are used to set up a summary of the type of participants that were present for the experiment. The other interview questions will be used to find if multiple people bring forth the same or similar criticisms, as well as to track if the feedback is deemed useful or clear.

8 EVALUATION RESULTS

For answering the question: “To what degree does concurrent haptic feedback, using a push metaphor, lead to an immediate (and lasting) change in body balance during front and back-stroke swimming practice using a wearable device.”, a study was conducted which consisted of the design and build of a wearable prototype with an IMU and haptic motors. This prototype was used in an experiment in which 18 people were asked to swim with and without haptic feedback on their body balance.

8.1 Participants

There are a total of 18 test participants of which 5 are female and 13 male. All the participants were either students or employees from the University of Twente. 6 were reported as beginners, 2 as average, 8 as intermediate and 2 as advanced. The interquartile range of the ages from 21 till 29 with the youngest being 19 and the oldest being 60.

8.1.1 Body awareness

A survey was conducted after each test condition of the experiment to test the body balance awareness. Figure 8.1 depicts these responses. The results in the figure are ordered from answered most agreeable to answered least agreeable. On the left side the different questions can be seen and in which phase they were answered. For instance, RetentionBS_Q3 shows the answers from question 3 that was asked right after the retention phase of the backstroke. Since BS and FS are found evenly distributed from the top to the bottom of the results in figure 8.1, it appeared that the overall body balance awareness did not differ between front crawl and backstroke swimming. The top of figure 8.1 is mostly occupied by questions that are answered after the feedback sessions. This suggests that the participants' responses were overall more favourable towards a higher awareness after performing a swimming bout with receiving haptic feedback which could indicate that the participants were most aware of their body balance when they received feedback. Q3 is an exception to the other 'feedback' questions. It is noteworthy to mention that Q3 is the only question that needed to be re-coded. The reported awareness after the retention session also seems higher than the reported awareness of the baseline condition. However this effect was less prominent than the awareness after the feedback session.

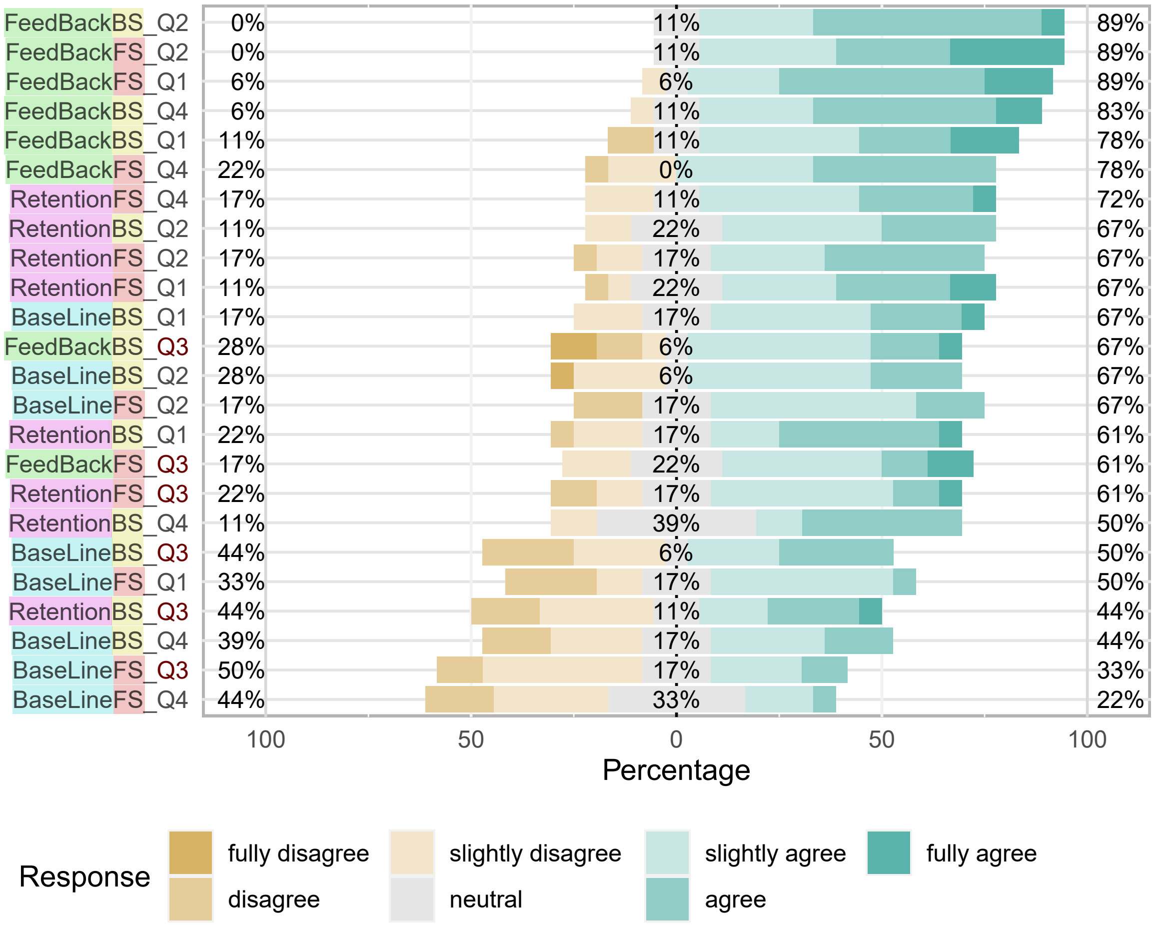


Figure 8.1: The answers to Q3 were re-coded (agree <-> disagree etc.). In green, pink and cyan the different test phases are marked to more easily identify how they agreeable they were answered. The red marked FS stands for 'freestyle', and the yellow marked BS stands for 'backstroke'. Q1: I actively adjust my body balance often; Q2: I notice when my body balance is flawed; Q3: I tend to forget my body posture; Q4: I am actively aware of the angle of my body

8.2 Statistical Analysis of RABA and TSUT

For performing an ANOVA test normality of the data needs to be assumed. For the RABA data this looked to be quite normal already. For the TSUT however it did not, the distribution seemed to be skewed to the left. To make the data more normal a root transform was applied. Due to zero values, there was still a tail on the left of the distribution (see for instance figure C.6). This diminishes the reliability of the results. In appendix C the TSUT data can be seen plotted in histograms, QQ-plots and boxplots, for every lane of all the participants separately and for the average TSUT per testphase per participant.

In table 8.1 the output of the post hoc paired wise t-test of the RABA and TSUT can be seen with a Bonferroni alpha compensation. However due to doing 4 tests, using another Bonferroni compensation, the adjusted p value should not exceed 0.05/4=0.0125. For the backstroke for the RABA and the TSUT only 1 significant difference was found across the data. That is between the RABA of the baseline test and the feedback test.

It was found that, for front crawl swimming, there is a significant increase in the RABA (swimming more straight) and decrease in TSUT (spending less time in a body angle that would result in receiving feedback) between the baseline and the feedback test-phases of the experiment.

.y.	group1	group2	n	statistic	df	p	p.adj	p.adj.signif
RABA	BaseLn-FS	FeedBk-FS	17	-3.38	16	0.004	0.012	*
RABA	BaseLn-FS	Reten-FS	17	-3.34	16	0.004	0.012	*
RABA	FeedBk-FS	Reten-FS	17	0.0460	16	0.964	1	ns
RABA	BaseLn-BS	FeedBk-BS	17	-3.43	16	0.003	0.01	*
RABA	BaseLn-BS	Reten-BS	17	-2.73	16	0.015	0.044	ns
RABA	FeedBk-BS	Reten-BS	17	2.10	16	0.052	0.156	ns
TSUT	BaseLn-FS	FeedBk-FS	17	3.59	16	0.002	0.007	*
TSUT	BaseLn-FS	Reten-FS	17	3.61	16	0.002	0.007	*
TSUT	FeedBk-FS	Reten-FS	17	-0.745	16	0.467	1	ns
TSUT	BaseLn-BS	FeedBk-BS	17	3.27	16	0.005	0.015	ns
TSUT	BaseLn-BS	Reten-BS	17	2.29	16	0.036	0.109	ns
TSUT	FeedBk-BS	Reten-BS	17	-2.94	16	0.01	0.029	ns

Table 8.1: Pairedwise t-test results of the RABA and the TSUT for front crawl (FS) and backstroke (BS) made using R. The p value is adjusted using the Bonferonni method.

Furthermore, for front crawl swimming, this change in RABA and TSUT was retained in the retention test-phase; directly after the feedback test phase. These results are reflected in figures 8.3 and 8.5.

For backstroke swimming no significant differences have been found except for the RABA between the baseline and the feedback test. This can been seen in figures 8.2 and 8.4. Overall, the participants had a smaller angle with regards to the water surface between these two test phases.

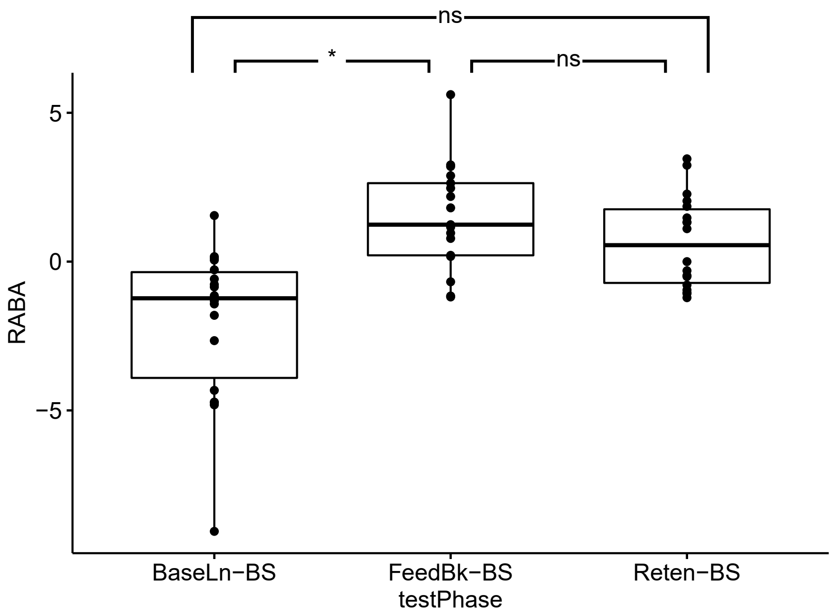


Figure 8.2: The RABA is the relative average body angle, this value is in degrees. The RABA of 17 participants is shown for three different test phases all swum in backstroke. A repeated measures ANOVA test was done on these values, form which it can be concluded that the overall difference in RABA between the baseline test and the feedback test was significant.

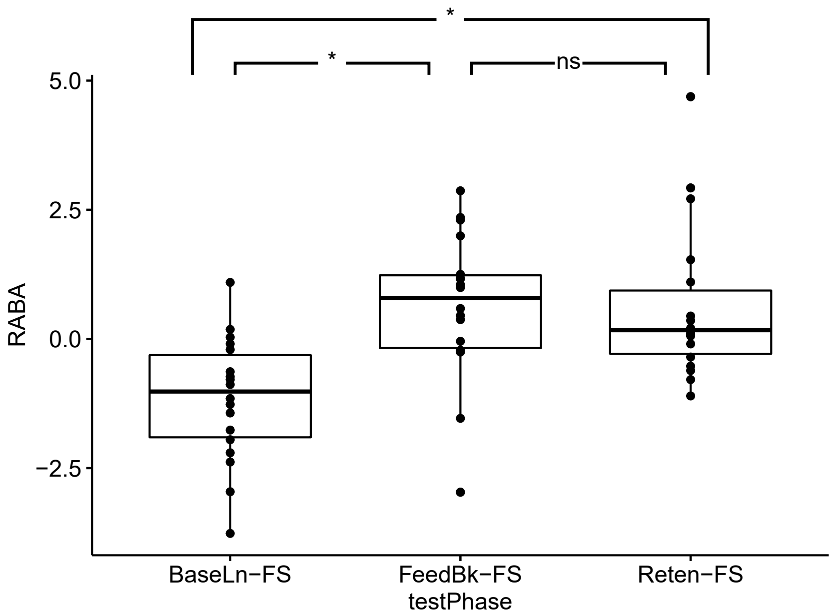


Figure 8.3: The RABA is the relative average body angle, this value is in degrees. The RABA of 17 participants is shown for three different test phases all swum in front crawl. A repeated measures ANOVA test was done on these values, form which it can be concluded that the overall difference in RABA between the baseline test and the feedback test was significant, As well as the overall difference between the Base line test and the retention test.

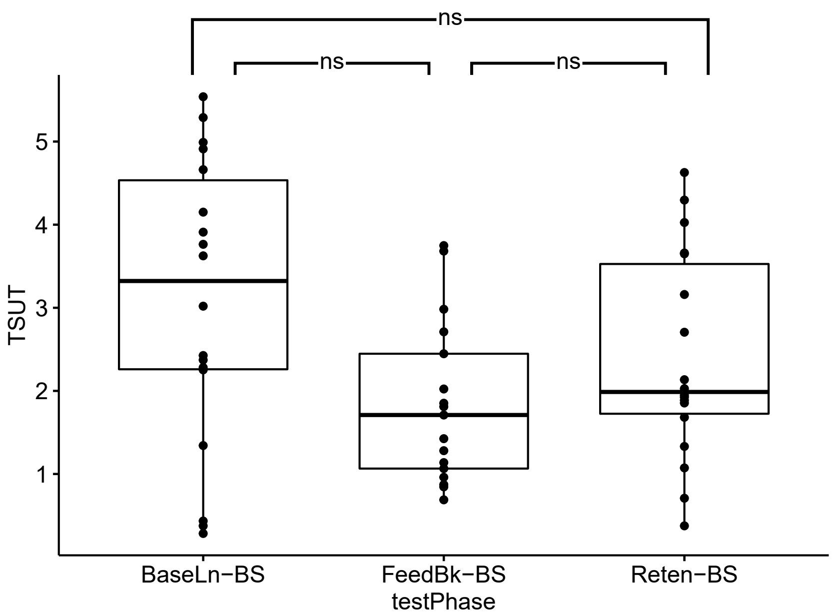


Figure 8.4: The TSUT is the time spend under threshold, the value was originally in seconds but has been root transformed to be in $s^{0.5}$ to adhere better to the normality assumption of the ANOVA. The ANOVA of 17 participants is shown for three different test phases all swum in backstroke. A repeated measures ANOVA test was done on these values, form which it can be concluded that the overall difference in TSUT between non of the test phases was significant.

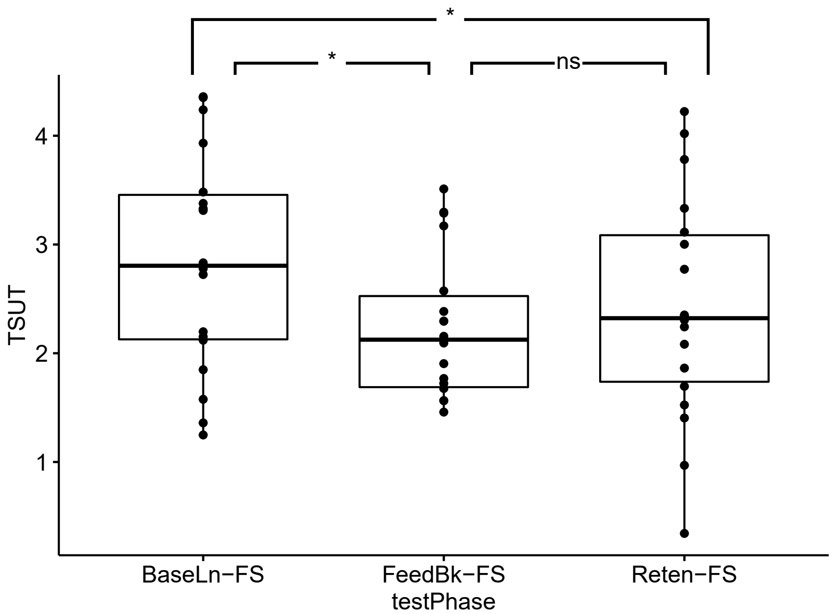


Figure 8.5: The TSUT is the time spend under threshold, the value was originally in seconds but has been root transformed to be in $s^{0.5}$ to adhere better to the normality assumption of the ANOVA. The ANOVA of 17 participants is shown for three different test phases all swum in front crawl. A repeated measures ANOVA test was done on these values, form which it can be concluded that the overall difference in TSUT between the baseline test and the feedback test was significant, As well as the overall difference between the Base line test and the retention test.

8.3 Interview results

After the test a short interview was conducted of around 2-3 minutes in time. The majority of the participants (14/18) overall thought that the feedback was useful (P 2, 4, 6, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19, 20) with quotes like:
”I think it is really useful to correct your posture.” - P6 (translated from Dutch),
”I liked the vibrating feedback a lot, because I noticed when my angle was off, so I had to go either more with my head in the water of use my legs more. I think I, it helped a lot.” - P17.
They reacted positively on the question if this wearable could help them become a better swimmer:
”I’d say yes, just for the fact that you are actively aware of what you’re doing. So, I often tend to forget my body position in the water, where if I’m actively thinking of it I can actively adjust to it.” - P13.
Also, most participants agreed that the feedback is clear (P 2, 5, 4, 8, 9, 12, 13, 14, 15, 17, 18, 19), some mention the feedback not being clear (P 1, 11, 20).
The criticism that was most repeated about the device was that it also reacted to the body roll (P 1, 5, 7, 10, 11, 12, 15, 17). Quite some people mentioned that the harness was uncomfortable or the wires were in the way (P 1, 4, 7, 8, 10). There were also four mentions of the feedback feeling random or unclear (P 1, 11, 17, 20). After that, the most touted criticism was that the device either worked better for the backstroke (P 10, 11, 20), or for the front crawl (P 2, 12, 14). In appendix D.1 to D.18 a summary of each interview can be read.

9 DISCUSSION

In this study research has been done into how to develop a wearable device that makes use of haptic feedback to improve swimming performance. This chapter contains a discussion on the different elements of the thesis.

9.1 Context

The study commenced with a context analysis in which literary research guided some design decisions and the research gap was clarified. Furthermore some initial testing for the feasibility of the hardware development was done.
One of the questions of the context analysis was how to implement feedback. Feedback needs to be accurate and relevant, appropriately timed and delivered, and decipherable by the athlete [62]. To have the feedback be accurate and relevant a suitable key variable was found; body balance. This variable is suitable because: it is measurable [74], it is adaptable by the athlete [59], and it is relevant since it is commonly done wrong among swimmers and detrimental to the performance if done wrong [24, 25]. Since swimming is a complex task it likely benefits from frequent feedback [3].
It was found that there were a few studies discussing five different implementations that focused on providing concurrent feedback during swimming [5, 6, 8, 9, 72]. One study performed a test with haptic feedback during swimming [7]. However, this test only tested if people reacted to haptics in a swimming environment, not if it would be useful as a training aid.
The reason for the limited amount of systems for concurrent augmented feedback during swimming might be due to the technical complexities of implementing solutions for concurrent haptic feedback [75], and the added difficulty of transferring existing solutions to an aquatic environment. Because of there already being a limited number of these implementation in this space, there have not been any published attempts making use of haptic feedback. This lack of the use of haptic feedback might be confounded because of it not being trivial to make it perceivable, as noticed from the performed perceivability test. Additionally, haptic feedback can open up the design space. Using the senses of sight or hearing causes either electronics to have to be mounted on the head [5, 6, 8, 72] or a special environment to be created [9]. Haptics allows more options where on the body to give the feedback and thus also were to use sensors without the use of wires or novel, experimental, wireless communication technologies [8]. For eventual consumer adoption, making a convenient device is essential [76]. This is also reflected in the few commercially available implementations that are found in this space, where it is as easy as putting on goggles, which is already part of a general routine [33, 34], or the product is sold as a research device [73], out of reach of the average consumer. Thus, the lack of haptics is a gap in the research of concurrent haptic feedback during swimming, which this study seeks to contribute to.

9.2 Restating the Research Questions

In the remaining sections of this chapter, the process of the study and the results of the experiments will be discussed and interpreted with regards to the research question:
RQ: How can a wearable device be designed to improve body balance in swimming with the use of haptic feedback?
This research question is supported by several sub questions that will also be discussed:

- SQ1: How can a wearable be made water resistant and provide haptic feedback?
- SQ2: How can a wearable be designed for multiple body types and as a platform to explore haptic metaphors?
- SQ3: How can body balance be measured using a wearable device?
- SQ4: How can haptic feedback be made perceivable in an aquatic swimming environment?
- SQ5: What kind of haptic metaphor can be used for providing feedback on the body balance?
- SQ6: How can the system be evaluated?
- SQ7: How does the system compare to the state of the art?

9.3 Development of the Wearable

One of the requirements to insure the possibility of a working prototype was that the wearable needed to be water resistant (SQ1). There seems to be no standard in literature for how to best go about water proofing a prototype [2]. The method used for this wearable is a combination of silicone linings that are poured in a separate 3D-printed mould, two part epoxy glue, silicone caulking and sufficient pressure between lids using screws and 3D-printed clips. This seems to keep water sufficiently away from the electronics. A choice was made to use Ni-MH batteries instead of more energy dense and smaller li-ion batteries for their smaller chance of violent chemical reactions.
Another important aspect of the functional form of the device was a mounting mechanism (SQ2). Based on early iterations of the prototype, it became apparent that elastic attachment mechanisms were required. The body of the wearers changed in size on the mounting location due to muscle movements. This, combined with the water drag would cause the wearable to shift around. The final prototype made use of a harness with adjustable elastic straps. There have been some comments on the wear comfort. Overall, participants did not report complaints regarding discomfort induced by the elastic straps.

9.4 Body Balance Measurement

For giving feedback on the body balance this first needs to be measured accurately (SQ3). For this, an IMU sensor is mounted on the back for measuring this angle. The wearable harness was designed to fix the location of the IMU as well as possible.
An angle calculation method was used by combining a trigonometric function on the accelerometer data and the integration of the gyroscope data over time. Previous research has used only the trigonometric function on the accelerometer [74], this works well to get a general value of the body balance performance over time. However, for real time applications, such a function can lead to inaccuracies during high acceleration movements. By also using the gyroscope, these sudden movements can be accounted for.

This method has successfully been used to differentiate between larger and smaller body angles in a preliminary test with only the researcher, and also during the evaluation test with eighteen participants.

A limitation of this algorithm is that the body angle and the body roll are compounded in the measurement in different amounts for different participants. This is due to the physiology of the back of the participants, and their body balance. When the sensor deviates further from being level, a rotation around the 'body roll axis' (vertical/polar axis) will add more to the measured outcome of the body angle. This increased the amount of feedback participants received, sometimes confusing participants into thinking the feedback is given on the body roll rather than the body angle. This can also be found back in the interviews with the participants. Furthermore, this compounding of the body roll with the body angle will not affect the RABA much, because larger deflections have little influence on the mean. However the TSUT will increase because of this effect for every time the deflection goes past the threshold value.

From the Benchmark test of the angle calculations also some limitations came to light. It took a significant time for the calculated value to come to a final value. This might have to do with the inaccuracies in the internal time delta calculations of the micro-controller, causing an initial under estimation of the actual rotation. In a way, this might have helped filter the data slightly and making the problem of the compounded body roll less severe.

9.4.1 RABA and TSUT as Key Performance Indicators

Physiological differences between participants can have a large impact on the the measurement of the body angle. For instance, a more hollow back causes the sensor to be in a different initial position which already gives an offset to the measured body angle. Because of these differences, it is difficult to define a measure based on absolute angle. Therefore, an experiment was designed where only relative improvements in body angle were compared. This was done using the RABA and the TSUT.

Next to that, RABA and TSUT are two methods of measuring the body balance. Bad body balance is a detrimental mistake that is mostly prominent among novice swimmers. More advanced swimmers often mostly eliminated their problems with body balance. Making the measure more suitable for novice swimmers.

The actual body balance performance is not visible in the data and thus differences between well performing participants and not well performing participants are very hard to distinguish. Thus the experimental design did not focus on how large the performance difference is between test conditions but rather if there is a difference. This enables to still quantitatively say something about the performance of the haptic feedback without resorting to large amounts of expert annotation of body balance performance for every participant.

The TSUT is not only dependent on the participant's abilities, but also on their individual preferences since the TSUT is dependent on the set threshold value. This causes a larger differentiation across participants since it seemed that participants have different preferences regarding the amount of feedback they prefer to receive. Some have a preference for more feedback whereas others would experience the same amount of feedback as "annoying". During the experiment a calibration sequence took place. For this calibration the participants were asked whether the amount of feedback they received was too little or too much. This method of calibration leaves a lot of room for subjective interpretation of what the right amount of feedback is. Thus the set feedback threshold will be relatively high for some and low for others. This makes the comparison of the TSUT between participants less focused and leads to a larger spread.

The reason for choosing relative variables such as the RABA and TSUT is because without outside-in sensing of the body or extensive annotations it is not feasible to find an absolute variable that relates to the body angle. Using a relative variable as RABA and TSUT opens up the possibility to still compare the performance of feedback between participants.

9.5 Development of the Haptics

For haptic feedback to be able to influence the swimmer, it needs to be perceivable (SQ4). The swimming environment possesses some challenges in this regard, since the water that flows along the body interferes with other haptic stimuli. A good method of solving this problem seemed to be to use fairly strong vibration motors to overcome the noise from the water current. There have been more problems with perceiving the feedback in the first tests than with the final evaluation experiment. This is likely due to the use of a different harness. With the newest revision the haptic motors are placed underneath an elastic band as supposed to being taped to the body. This extra pressure has likely helped making the vibrations be perceived as stronger. There are countless of possible combinations of patterning, placing and intensity. Due to this scope, it is not feasible to test every combination. To still come to a suitable metaphor, first a perceivability test was done on multiple body locations. This test was only done with the researcher. After that, the most promising body locations were tested with three other participants. For the haptic patterning three different methods were tried. From this it became clear that the preferred patterns were also perceived as easiest to interpret. In this case the most perceivable locations (sensitive to haptic feedback in a swimming environment) with continues vibrating when doing something wrong. There was a little discrepancy between participants what the most perceivable location was to them. The test participants had difficulty distinguishing between the binary (only fully on or fully off) and ramping (increasing intensity with increased error) feedback, however called the ramping feedback less random. So this was eventually chosen for further testing.

9.6 Evaluation of Haptic Feedback in Swimming

To evaluate the system, the main focus was on the working principle of concurrent haptic feedback during swimming (SQ6). For this an experiment was set up with a more specific research question: *"To what degree does concurrent haptic feedback, using a push metaphor, lead to an immediate and lasting change in body balance during front crawl and backstroke swimming practice using a wearable device."*
For practical reasons, it has been assumed for this research that the best possible body balance performance is when the angle to the surface of the water is smallest. The actual optimal posture when swimming is incredibly complex, dependent on the anatomy of the swimmer, and the speed going through the water [77]. This study only compares the difference between body angle without or with a concurrent haptic feedback intervention.

9.6.1 Interpretation of the Evaluation Results

The results imply that, for front crawl swimming, the haptic feedback device has an immediate desirable effect on the motor acquisition of body balance. Receiving concurrent haptic feedback on the body angle with a push metaphor seems to help with maintaining a more correct posture during front crawl swimming. The results in the retention phase also shows improvement for RABA and TSUT, which suggests that, after having experienced the feedback from the haptic device, body awareness increases and is retained to some degree. At least for the immediate several minutes after the feedback phase. In the freestyle condition, a significant difference between the baseline, feedback, and retention test phases are observed. In the backstroke condition, similar trends were seen, however the differences were not statistically significant. It is known that relatively large sample sizes are required to reliably conduct statistical tests with linear mixed-effects models [78]. Hence, it is probable that the lack of significance was attributable to the small sample size. Replication of the study with a larger group may cause sufficient power to be attained to detect a statistically significant effect.

From the interviews, it seemed that the participants were mostly positive about the usefulness of the intervention and the wearable device. This might imply that the resistance for adoption of such a device is low, at least the specific tested population consisting of mainly University of Twente students. Participants also reported a higher body balance awareness with the intervention than without. This might have contributed to the positive sentiment towards the intervention.

9.6.2 Body Awareness Measurements

The results from the body balance awareness measurements are solely to support the hypotheses that haptic feedback leads to a higher body balance awareness. The questionnaire was validated by a group of Interaction Technology students. They were asked what measure a group of questions would test for, and which of the questions tested this measure the best. A confirmatory factor analysis would have helped to see if the survey would have tested for a singular measure. However, due to the sample size, the degree of freedom was too low to perform such a test. The small sample size also caused large differences between results that were difficult to explain when performing a Cronbach's Alpha test. For instance, when testing the Cronbach's Alpha for the feedback test, the difference for front crawl and backstroke swimming was 0.66. This could be explained if the interpretation of the questions relied heavily on the swim-stroke. However, this large deviation between Cronbach's Alphas is not seen in other test-phases. Hence, due to the unreliable results of the formal statistical tests, the data was analysed purely descriptively. Furthermore, the results might have suffered from confirmation bias; based on the questions, participants could infer that they were supposed to score higher when participating in the feedback test. Also, the third question was the only one which was posed negatively. The participants may have assumed that answering more agreeable would mean a higher body balance awareness. This might have led to the results differing from the expected outcome compared to the other questions (the feedback round receiving highest scores). Lastly, eleven of the participants received the survey in colour, with the colours ranging from red to green. This might have biased the data with people perceiving green as more positive.

9.6.3 Fatigue and Training Effect

In the experiment as it is set up, there are two confounding variables that influence how the data should be interpreted: fatigue and learning effect. Fatigue can cause the body balance to suffer as the experiment progresses. This effect is most noticeable within a test phase, where a participants' body falls deeper in the water as the participant gets further within their swimming bout. A short rest in between the swimming bouts causes some swimmers to start at a better body balance at the beginning of their next swimming bout. The effects of fatigue over the course of the whole experiment are less obvious but very likely still present, influencing the body balance more in the later test phases, especially in the retention phase. Furthermore, the swim endurance of the different participants is very important to the effect of fatigue. The implications of this are that any changes in body balance performance are across test phases can be under or over estimated. Spreading the test over several days will reduce this fatigue effect.

In the results (for the front crawl swimming), a significant improvement in body balance is measured between the baseline and feedback test phases. Furthermore, there is a positive improvement between the baseline and the retention test phases. This likely implies that the intervention had a positive influence on participants' body balance. However, this cannot be stated conclusively due to confounding with training effects. An increase in performance could be observed as a result of training, regardless of the presence of an intervention. Therefore, a causal relation between performance increase and the effectiveness of the intervention cannot be assumed. Even though learning swimming takes much longer than just a 45 - 60 minutes session. So the influence of a training effect is postulated to be small.

9.7 Comparison with Similar Systems

To argue for the contribution of this study to the research of feedback systems in swimming it can be compared to similar systems (SQ7). Presumably, the wearable discussed in this study is the first concurrent feedback system for swimming that makes use of haptics as the feedback modality. Contrary to the other systems [5, 6, 8, 9, 72, 33, 34] in this category, no electronics need to be mounted on the head, or the regular swimming environment does not have to be radically altered. This is very beneficial for keeping loose wires at a minimum. For this version of the prototype, loose wires were used to keep the possibility for haptic metaphor exploration. These can be omitted however in a future prototype.

Most systems in this category are promising [5, 9], or proofed useful [72, 6], in aiding in swim training. So too does the prototype developed for this study. This lends weight to the concept of regular use of concurrent feedback technology in swimming.

The key variables that are measured by similar systems are: the hand pressure [9, 72], the speed variability [6], the anteroposterior hip acceleration [5], and the stroke rate [8, 33, 34]. The difference between these key variables and the use of body balance for the key variable is that body balance is mainly a problem among novice swimmers and the other variables are still trained by intermediate and advanced swimmers. This means that the implementation of the prototype as it stands only allows for a short period of use for any particular swimmer.

10 CONCLUSIONS

In this paragraph some concluding statements will be given with regards of the development of wearable as well as some newly acquired knowledge about the use of concurrent haptic feedback in a swimming environment and specifically about the implementation of haptic feedback used in this study.

SQ1: How can a wearable be made water resistant and provide haptic feedback? Making a wearable water tight can be done using 3D printing and a silicone or epoxy lining. This is a great way to go about the design of such a prototype, if the developer of this prototype is well-versed in the use of these kind of materials. It offers a great deal of customization and fairly rapid changes.

SQ2: How can a wearable be designed for multiple body types and as a platform to explore haptic metaphors? Care was put into making the wearable suitable as a platform for testing haptic feedback in a swimming environment. Adjustable elastic straps are a good method for keeping the wearable in its place and making a wearable that multiple people can wear. Straps without any elastics should be avoided, since they will shift around. Having the haptic motors on a cable makes the exploration of multiple haptic metaphors possible. During testing it was discovered that using tape to secure them to the body is not ideal for applying haptic feedback, since some pressure is needed to be able to perceive the vibrations well.

SQ3: How can body balance be measured using a wearable device? A singular sensor with a simple angle calculation algorithm can be used to measure the body angle sufficiently well for concurrent haptic feedback. A thing to look out for when measuring the body balance is the body roll motion. Many participants experienced false positive feedback due to this motion being recognised as a change in body angle to the point that some believed this to be the key variable that was given feedback on. An effort of removing this compounding behaviour should be made.

SQ4: How can haptic feedback be made perceivable in a aquatic swimming environment? The use of 12mm cylindrical eccentric haptic motors that ran on 3.8V were sufficient to be perceived on the ribs. A rule of thumb when choosing a location for haptic feedback during swimming is: if the body location experiences a large amount of turbulent water flow, there is likely a need for stronger vibrations and/or more pressure.

SQ5: What kind of haptic metaphor can be used for providing feedback on the body balance? The haptic metaphor used was a push metaphor on the ribs with an increase of intensity of vibration for the first few degrees of the body angle, and fully on for larger errors in the body angle. This seemed to be a good haptic metaphor since no participant seemed to have had problems understanding what the metaphor meant. Modulation of the haptic pattern in the time domain seemed to confuse the participants. Therefore, this may be avoided whenever possible.

SQ6: How can the system be evaluated? Although some of the design choices of the evaluation experiment could still be questioned, there was a statistically significant improvement in body balance between the feedback and the baseline test conditions for front crawl swimming. Furthermore, it could be observed that the awareness of their body balance has improved during the experiment. Additionally, participants generally believed that the feedback was not distracting and many reported that it could be helpful. In short, there is evidence that concurrent haptic feedback, using a push metaphor, leads to an immediate change in body balance during front crawl swimming practice.

SQ7: How does the system compare to the state of the art? The use of haptics in concurrent feedback applications for swimming is novel. The use of haptic feedback as compared to auditory or visual feedback opens up new possibilities for wearable design in this space. For instance, electronics do not need to be mounted on the head and there is more freedom for sensor placement while eliminating loose wires.
Similar to many other applications for concurrent feedback during swimming, the developed prototype seems to contribute positively to improving swim performance, supporting the idea of developing and normalising feedback technology applications for swimming.

This thesis has reported on the context surrounding concurrent haptic feedback in swimming and on the development and validation of a working prototype that aimed to improve body balance in swimmers using concurrent haptic feedback during swimming. The methods of development of this wearable device can help guide decisions for the development of similar devices. The use of haptic feedback during swimming was a mostly unexplored field of research. This study shows that there is valid potential for the use of concurrent haptic feedback for teaching swimming and that lessons learned in this thesis have helped shape this potential.

11 RECOMMENDATIONS

For measuring the change in body angle accurately it is best to take out the body roll component as much as possible. As of the writing of this thesis, the calculation of the body angle does not take into account the natural angle the swimmer, and thus also the IMU, will be laying in. An effort should be made to take into account and the body roll to separate it more clearly from the body angle. This would result in a more accurate body angle measurement which causes the wearable to give more accurate feedback and can result in less confusion among participants.
This research has shown that there is potential in the use of haptic feedback to teach swimming technique. For a more conclusive test for the effectiveness, a similar method can be used as been used in testing for a different wearable feedback device [72]. The test participants should divided into two groups of equal performance in body balance judged by experts. The control group (A) should then do a few training sessions over a longer period of time without augmented feedback whilst the other group (B) does a similar training with augmented feedback. Thereafter, the control group can repeat the training with augmented feedback (A'). The feedback is likely effective if both the group B and group A' perform significantly better than group A. To increase the strength of the results for such an experiment, there can also be a placebo group to differentiate between motor learning and motor acquisition [79].
Something that has just fallen outside of the scope of this study, is to have a more qualitative look at the individual results of the evaluation test. Patterns are to be found in participants with a similar level or differences between the RABA and TSUT performance. These patterns can lead to questions to perform future research on.
For the study as it stands now, a single haptic metaphor was tested on one key variable. This metaphor was decided on through testing with four different users. The used hardware has the potential to be used for many more haptic metaphors. For instance, body roll could be a key variable that is relatively easily measured. The body roll needs to be not too great or to small and ideally rather constant for reducing drag and increasing muscle activation [10]. With the use of two independent motors feedback can be given on depending on which side the swimmer rolls to.
Another interesting key variable is hand pressure. Research have shown significant improvements in swimming performance with concurrent haptic feedback on this variable [6, 9, 72]. By integrating haptics in in this concept the size can be reduced and convenience of use can be improved. This improves the commercial viability for consumers [76] and might normalise the concept of concurrent feedback for swimming. The challenge will again lay in making this haptic feedback perceivable.
The wearable as it stands was designed to test immediate changes of body balance from haptic feedback. For this, the decision was made to not include some ease of use features for the wearable due to the thesis scope. However, for a longer study, features like: automatic stroke detection, easily accessible interface (for the user), and a way of turning off the device without taking out the battery, could be essential for participants not to get frustrated. Presumably, the stroke type detection is easily implemented by running the collected data recordings through a machine learning model. The device already has dedicated hardware to run simple decision trees.
One of the things that would help compare body balance between participants if it can be mea-

sured in a more absolute way. Right now, the RABA is used to compare between participants, but this only show the relative improvement within a subject. It is not indicative of the actual performance. Finding a way to measure the body balance that is is indicative of performance also opens up the possibility to compare whether such an intervention works only for beginners or also for more advanced swimmers.
The prototype as it stands now is not developed for a general consumer. Some aspects of the requirements wheel from [69] depicted in figure 2.5 were overlooked intentionally to quicken the design and testing. From the tests it can be inferred that aesthetics, engagements, safety and, for most, comfort were quite well received. If a production version of a swimming wearable with haptic feedback would be created, it will mainly need to improve the cognitive ergonomics. The usability could be solved with a user interface that does not rely on a second person to interact with. A small user interface on the front of the device consisting of a few buttons and a screen will make the wearable usable autonomously.

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A PROTOTYPE LOGGING FIRST DATA MICRO PYTHON SCRIPT

This code was derived form an Adafruit tutorial (https://learn.adafruit.com/getting-started-with-raspberry-pi-pico-circuitpython/data-logger) and changed to suit the needs of this research

```
"""
Data logging example for Pico. Logs the temperature to a file on the Pico.
"""
import time
import board
import digitalio
import busio as io
import microcontroller
import adafruit_mpu6050
from analogio import AnalogIn

led = digitalio.DigitalInOut(board.LED)
led.switch_to_output()

i2c = io.I2C(scl=board.GP7, sda=board.GP6)
mpu = adafruit_mpu6050.MPU6050(i2c)

time.sleep (2)
led.value = not led.value
time.sleep(0.12)
led.value = not led.value
time.sleep(0.12)
led.value = not led.value
time.sleep(0.12)
led.value = not led.value
time.sleep(0.12)
led.value = not led.value
time.sleep(0.12)
led.value = not led.value

dataArray = []
while True:
    while len(dataArray) < 400:
            dataArray.append("%.2f,%.2f,%.2f,"%(mpu.acceleration) + "%.2f,%.2f,%.2f
    "%(mpu.gyro) + '\n')
            time.sleep(0.02)
    try:
        with open("/IMUdata.txt", "a") as datalog:
            for newLine in dataArray:
                datalog.write(newLine)
            datalog.flush()
            dataArray = []
            led.value = not led.value
    except OSError as e:  # Typically when the filesystem isn't writeable...
        delay = 1  # ...blink the LED every half second.
        if e.args[0] == 28:  # If the filesystem is full...
            delay = 0.25  # ...blink the LED faster!
```

```
        while True:
            led.value = not led.value
            time.sleep(delay)
```

B ARDUINO CODE

SwimmingWearableRev3.ino

```
#include "interactionFunctions.h"
#include "IMUFunctions.h"
#include "dataLoggingFunctions.h"
#include "lightPatterns.h"

#define STANDBY 1
#define CHANGEFBMODE 2
#define CHOSENHARDFB 3
#define CHOSENSOFTFB 4
#define RECORDMODE 5
#define RECORDMODEWITHFB_FS 6
#define RECORDMODEWITHFB_BS 7
#define FROMFSTOBS 8
#define FROMBSTOFS 9
#define CALIBRATE_FS 10
#define CALIBRATE_BS 11
#define ADJUSTCALIBRATIONUP_FS 12
#define ADJUSTCALIBRATIONDOWN_FS 13
#define ADJUSTCALIBRATIONUP_BS 14
#define ADJUSTCALIBRATIONDOWN_BS 15
//haptic modes
#define HAPTICS_HARD 0
#define HAPTICS_SOFT 1
;
unsigned long IMUPollingTimer = 0;
unsigned long actionTimer = 0;
unsigned long prevTime = 0;
int buttonTimer = 0;
bool indicatorLED = 0;
int state = 0;
int hapticState = 0;
int plotterState = 0;

void setup() {
  Serial.begin(115200);
  initButton();
  initHapticEngine();
  intitIMU();
  initSDcard();
  state = STANDBY;
}

void loop() {
  //Serial.println(digitalRead(7));
  if (state != STANDBY) {
    readIMU();
    calculatePitchAngle();
  }
  listenToButton(100, 10);
  switch (state) {
```

```
    case STANDBY:
      updateStatusLight(100, blueFadeInOut, 35);
      if (buttonAction == MEDIUMPRESS) {
        state = RECORDMODE;
        findNewFileName();
        openNewSDFile();
      }
      if (buttonAction == DOUBLEPRESS) {
        state = RECORDMODEWITHFB_FS;
        findNewFileName();
        openNewSDFile();
        enableHapticEngine();
      }
      if (buttonAction == TRIPLEPRESS) {
        state = RECORDMODEWITHFB_BS;
        findNewFileName();
        openNewSDFile();
        enableHapticEngine();
      }
      if (buttonAction == LONGPRESS) {
        state = CHANGEFBMODE;
      }
      break;
    case CHANGEFBMODE:
      updateStatusLight(100, blueThreeFlashes, 8);
      if (buttonAction == DOUBLEPRESS) {
        state = CHOSENHARDFB;
        hapticState = HAPTICS_HARD;
        actionTimer = millis();
      }
      if (buttonAction == TRIPLEPRESS) {
        state = CHOSENSOFTFB;
        hapticState = HAPTICS_SOFT;
        actionTimer = millis();
      }
      break;
    case CHOSENSOFTFB:
      if (millis() < actionTimer + 2400) {
        updateStatusLight(100, blueToGreenTwoBlip, 24);
      }
      else {
        state = STANDBY;
      }
      break;
    case CHOSENHARDFB:
      if (millis() < actionTimer + 2400) {
        updateStatusLight(100, blueToRedTwoBlip, 24);
      }
      else {
        state = STANDBY;
      }
      break;
    case RECORDMODE:
      if (millis() > IMUPollingTimer + 19) {
        IMUPollingTimer = millis();
        writeSDIMUlog(convertIMUtoString(IMUdata));
      }

      if (!writingError) {
        updateStatusLight(100, greenFadeInOut, 35);
      }
      else {
        updateStatusLight(200, redThreeFlashes, 8);
```

```
      }

      if (buttonAction == LONGPRESS) {
        closeSDlog();
        state = STANDBY;
      }
      break;
    case RECORDMODEWITHFB_FS:
      if (hapticState == HAPTICS_HARD) {
        binaryAngleHapticEngine(pitch, calibrationValue_FS);
      } else {
        continuesAngleHapticEngine(pitch, calibrationValue_FS, calibrationValue_FS - 3);
      }
      if (millis() > IMUPollingTimer + 19) {
        IMUPollingTimer = millis();
        writeSDIMUlog(convertIMUtoString(IMUdata));
      }
      if (!writingError) {
        updateStatusLight(100, redFadeInOut, 35);
      }
      else {
        updateStatusLight(200, redThreeFlashes, 8);
      }

      if (buttonAction == SHORTPRESS) {
        state = ADJUSTCALIBRATIONUP_FS;
        actionTimer = millis();
      }
      else if (buttonAction == MEDIUMPRESS) {
        state = ADJUSTCALIBRATIONDOWN_FS;
        actionTimer = millis();
      }
      else if (buttonAction == TRIPLEPRESS) {
        state = CALIBRATE_FS;
        calibrationTimer = millis();
      }
      else if (buttonAction == DOUBLEPRESS) {
        state = FROMFSTOBS;
        actionTimer = millis();
      }
      else if (buttonAction == LONGPRESS) {
        closeSDlog();
        state = STANDBY;
      }
      break;
    case CALIBRATE_FS:
      if (!calibrated) {
        calibration(pitch);
      }
      else {
        closeSDlog();
        writeSDcalibrationValueLog(calibrationValue - 18.2);
        closeSDlog();
        calibrationValue_FS = calibrationValue - 18.2;
        state = RECORDMODEWITHFB_FS;
        calibrated = false;
        analogWrite(4, 255);
        analogWrite(7, 255);
        analogWrite(6, 0);
        analogWrite(3, 0);
        delay(500);
        analogWrite(4, 0);
```

```
        analogWrite(7, 0);
        analogWrite(6, 255);
        analogWrite(3, 255);
        delay(500);
        analogWrite(4, 0);
        analogWrite(7, 0);
        analogWrite(6, 0);
        analogWrite(3, 0);
        openNewSDFile();
      }
      break;
    case ADJUSTCALIBRATIONUP_FS:
      if (millis() < actionTimer + 493) {
        updateStatusLight(29, greenRampUp, 17);
      }
      else {
        state = RECORDMODEWITHFB_FS;
        closeSDlog();
        calibrationValue_FS += 1.5;
        writeSDcalibrationValueLog(calibrationValue_FS);
        closeSDlog();
        openNewSDFile();
      }
      break;
    case ADJUSTCALIBRATIONDOWN_FS:
      if (millis() < actionTimer + 493) {
        updateStatusLight(29, greenRampDown, 17);
      }
      else {
        state = RECORDMODEWITHFB_FS;
        closeSDlog();
        calibrationValue_FS -= 1.5;
        writeSDcalibrationValueLog(calibrationValue_FS);
        closeSDlog();
        openNewSDFile();
      }
      break;
    case RECORDMODEWITHFB_BS:
      if (hapticState == HAPTICS_HARD) {
        binaryAngleHapticEngine(pitch, calibrationValue_BS);
      } else {
        continuesAngleHapticEngine(pitch, calibrationValue_BS, calibrationValue_BS -
    10);
      }

      if (millis() > IMUPollingTimer + 19) {
        IMUPollingTimer = millis();
        writeSDIMUlog(convertIMUtoString(IMUdata));
      }
      if (!writingError) {
        updateStatusLight(100, yellowFadeInOut, 35);
      }
      else {
        updateStatusLight(200, redThreeFlashes, 8);
      }

      if (buttonAction == SHORTPRESS) {
        state = ADJUSTCALIBRATIONUP_BS;
        actionTimer = millis();
      }
      else if (buttonAction == MEDIUMPRESS) {
        state = ADJUSTCALIBRATIONDOWN_BS;
        actionTimer = millis();
```

```
      }
      else if (buttonAction == TRIPLEPRESS) {
        state = CALIBRATE_BS;
        calibrationTimer = millis();
      }
      else if (buttonAction == DOUBLEPRESS) {
        state = FROMBSTOFS;
        actionTimer = millis();
      }
      else if (buttonAction == LONGPRESS) {
        closeSDlog();
        state = STANDBY;
      }
      break;
    case CALIBRATE_BS:
      if (!calibrated) {
        calibration(pitch);
      }
      else {
        closeSDlog();
        writeSDcalibrationValueLog(calibrationValue + 17.8);
        closeSDlog();
        calibrationValue_BS = calibrationValue + 17.8;
        state = RECORDMODEWITHFB_BS;
        calibrated = false;
        analogWrite(4, 255);
        analogWrite(7, 255);
        analogWrite(6, 0);
        analogWrite(3, 0);
        delay(500);
        analogWrite(4, 0);
        analogWrite(7, 0);
        analogWrite(6, 255);
        analogWrite(3, 255);
        delay(500);
        analogWrite(4, 0);
        analogWrite(7, 0);
        analogWrite(6, 0);
        analogWrite(3, 0);
        openNewSDFile();
      }
      break;
    case ADJUSTCALIBRATIONUP_BS:
      if (millis() < actionTimer + 493) {
        updateStatusLight(29, greenRampUp, 17);
      }
      else {
        state = RECORDMODEWITHFB_BS;
        closeSDlog();
        calibrationValue_BS += 1.5;
        writeSDcalibrationValueLog(calibrationValue_BS);
        closeSDlog();
        openNewSDFile();
      }
      break;
    case ADJUSTCALIBRATIONDOWN_BS:
      if (millis() < actionTimer + 493) {
        updateStatusLight(29, greenRampDown, 17);
      }
      else {
        state = RECORDMODEWITHFB_BS;
        closeSDlog();
        calibrationValue_BS -= 1.5;
```

```
        writeSDcalibrationValueLog(calibrationValue_BS);
        closeSDlog();
        openNewSDFile();
      }
      break;
    case FROMFSTOBS:
      if (millis() < actionTimer + 1000) {
        updateStatusLight(40, redFadeToGreen, 25);
        if (millis() < actionTimer + 200) {
          hapticOn();
        }
        else if (millis() < actionTimer + 700) {
          hapticOff();
        }
        else {
          hapticOn();
        }
      }
      else {
        closeSDlog();
        writeSDcalibrationValueLog(calibrationValue_BS);
        closeSDlog();
        state = RECORDMODEWITHFB_BS;
        openNewSDFile();
        hapticOff();
      }
      break;
    case FROMBSTOFS:
      if (millis() < actionTimer + 1000) {
        updateStatusLight(40, greenFadeToRed, 25);
        if (millis() < actionTimer + 300) {
          hapticOn();
        }
        else if (millis() < actionTimer + 800) {
          hapticOff();
        }
        else {
          hapticOn();
        }
      }
      else {
        closeSDlog();
        writeSDcalibrationValueLog(calibrationValue_FS);
        closeSDlog();
        state = RECORDMODEWITHFB_FS;
        openNewSDFile();
        hapticOff();
      }
      break;
  }
}
```

interactionFunctions.h

```
#include <NeoPixelConnect.h>
//--------------------------------------------------------------------------------
//-------------------------------Haptic Engine Code-------------------------------
//--------------------------------------------------------------------------------

void initHapticEngine() {
  pinMode(7, OUTPUT); //IN1
  pinMode(6, OUTPUT); //IN2
  pinMode(5, OUTPUT); //EN

```

```
  pinMode(4, OUTPUT); //IN1
  pinMode(3, OUTPUT); //IN2
  pinMode(2, OUTPUT); //EN

  digitalWrite(7, LOW);
  digitalWrite(6, LOW);
  digitalWrite(5, LOW);

  digitalWrite(4, LOW);
  digitalWrite(3, LOW);
  digitalWrite(2, LOW);
}

void enableHapticEngine() {
  digitalWrite(5, HIGH);
  digitalWrite(2, HIGH);
}

void disableHapticEngine() {
  digitalWrite(5, LOW);
  digitalWrite(2, LOW);
}

void hapticOff() {
  analogWrite(4, 0);
  analogWrite(7, 0);
}

void hapticOn() {
  analogWrite(4, 255);
  analogWrite(7, 255);
}
unsigned long hapticTimer = 0;
bool hapticIsOn = false;

void blinkHapticEngine() {
  if (millis() > hapticTimer + 1000) {
    hapticTimer = millis();
    if (hapticIsOn) {
      analogWrite(4, 255);
      analogWrite(7, 0);
    }
    else {
      analogWrite(4, 0);
      analogWrite(7, 255);
    }
    hapticIsOn = !hapticIsOn;
    Serial.println(hapticIsOn);
  }
}

void backAndForthHapticEngine() {
  if (millis() > hapticTimer + 1000) {
    hapticTimer = millis();
    if (hapticIsOn) {
      analogWrite(4, 255);
      analogWrite(7, 255);
      analogWrite(6, 0);
      analogWrite(3, 0);
    }
    else {
      analogWrite(4, 0);
      analogWrite(7, 0);
```

```
      analogWrite(6, 255);
      analogWrite(3, 255);
    }
    hapticIsOn = !hapticIsOn;
    Serial.println(hapticIsOn);
  }
}

byte analogHapticValue = 0;

void rampUpHapticEngine() {
  if (millis() > hapticTimer + 100) {
    hapticTimer = millis();
    analogWrite(7, analogHapticValue);
    analogHapticValue += 2;
  }
}

void continuesAngleHapticEngine(float pitch, float minTreshold, float maxTreshold) {
  if (pitch < minTreshold && pitch > maxTreshold) {
    int strength = map(pitch, minTreshold, maxTreshold, 0, 255);
    analogWrite(7, strength);
    analogWrite(4, strength);
  }
  else if (pitch > -50 && pitch < minTreshold) {
    hapticOn();
  }
  else {
    hapticOff();
  }
}

void binaryAngleHapticEngine(float pitch, float treshold) {
  if (pitch < treshold && pitch > -50) {
    hapticOn();
  }
  else {
    hapticOff();
  }
}

float pastPitch = 0;

void IncreaseFrequency(float pitch, float maxTreshold, float minTreshold) {
  if (pitch > minTreshold && pitch < maxTreshold) {
    int pulseLength = map(pitch, minTreshold, maxTreshold, 200, 20);
    if (millis() > hapticTimer + pulseLength) {
      hapticOff();
      if (millis() > hapticTimer + pastPitch) {
        hapticTimer = millis();
        pastPitch = map(pitch, minTreshold, maxTreshold, 200, 1500);
      }
    }
    else {
      hapticOn();
    }
  }
  else if (pitch > -35 && pitch < minTreshold) {
    hapticOn();
  }
  else {
    hapticOff();
  }
```

```
}

//------------------------------------------------------------------------------------
//--------------------------------Status Light Code---------------------------------
//------------------------------------------------------------------------------------

void updateStatusLight(int, byte []);
NeoPixelConnect LED(28, 1);
unsigned long lightTimer = 0;
int lightSequenceCounter = 0;

void updateStatusLight(int lightRefreshRate, byte lightSequence[][3], byte
    sizeOfArray) {
  if (millis() > lightTimer + lightRefreshRate) {
    lightTimer = millis();
    if (sizeOfArray - 1 > lightSequenceCounter) {
      LED.neoPixelFill(
        lightSequence[lightSequenceCounter][0],
        lightSequence[lightSequenceCounter][1],
        lightSequence[lightSequenceCounter][2],
        true
      );
      lightSequenceCounter++;
    }
    else {
      LED.neoPixelFill(
        lightSequence[lightSequenceCounter][0],
        lightSequence[lightSequenceCounter][1],
        lightSequence[lightSequenceCounter][2],
        true
      );
      lightSequenceCounter = 0;
    }
  }
}

//------------------------------------------------------------------------------------
//-------------------------------Calibration sequence------------------------------
//------------------------------------------------------------------------------------

unsigned long calibrationTimer;
float calibrationValue_FS = 0;
float calibrationValue_BS = 0;
float calibrationValue;
int calibrationSampleCount = 0;
int calibrationWaitTime = 3000;
int calibrationCaptureTime = 1000;
bool calibrated = false;
bool message1 = false;
byte waitForCalibrationLight[2][3] = {{0, 255, 0}, {0, 0, 0}};
byte calibratingLight[2][3] = {{0, 0, 255}, {0, 0, 0}};
byte samplingLight[2][3] = {{255, 0, 0}, {0, 0, 0}};


void calibration(float pitch) {
  if (pitch < 45 && pitch > -45) {
    if (millis() > calibrationTimer + calibrationWaitTime) {
      if (millis() < calibrationTimer + calibrationWaitTime + calibrationCaptureTime
    ) {
        updateStatusLight(100, samplingLight, 2);
        calibrationValue += pitch;
        calibrationSampleCount++;
        Serial.print("Collecting sample: ");
```

```
        Serial.println(calibrationSampleCount);
      }
      else {
        calibrationValue = (calibrationValue / calibrationSampleCount);
        Serial.print("Final calibration value: ");
        Serial.println(calibrationValue);
        calibrationTimer = millis();
        calibrationSampleCount = 0;
        calibrated = true;
        message1 = false;
      }
    }
    else {
      if (!message1) {
        Serial.println("Waiting for calibration Start");
        calibrationValue = 0;
      };
      message1 = true;
      updateStatusLight(200, calibratingLight, 2);
    }
  }
  else {
    updateStatusLight(500, waitForCalibrationLight, 2);
    calibrationTimer = millis();
  }
}

//----------------------------------------------------------------------------------
//-----------------------------------Button code-----------------------------------
//----------------------------------------------------------------------------------

#define BUTTON_PIN 8

#define NOACTION 0
#define SHORTPRESSBUSY 1
#define SHORTPRESS 2
#define MEDIUMPRESSBUSY 3
#define MEDIUMPRESS 4
#define LONGPRESSBUSY 5
#define LONGPRESS 6
#define DOUBLEPRESS 7
#define TRIPLEPRESS 8

void initButton() {
  pinMode(BUTTON_PIN, INPUT_PULLUP);
}

byte buttonAction = 0;
byte pressCounter = 0;
unsigned long buttonPollingTimerSlow = 0;
unsigned long buttonPollingTimerFast = 0;
unsigned int interactionTimeLimit = 500; //max time between buttonpresses and before
     returning to slow polling in milliseconds
unsigned int interactionTimer = 0; //counts up how long an interaction is happening
unsigned int timeMediumPress = 1000; //has to be larger than interactionTimeLimit
unsigned int timeLongPress = 3000; //has to be larger than interactionTimeLimit and
    timeMediumPress
bool buttonReleased = false;
bool buttonPressed = false;
bool fastPolling = false;

void digitalReadButton() {
  if (!digitalRead(BUTTON_PIN)) {
```

```
    buttonPressed = true;
  }
  else {
    buttonPressed = false;
  }
  //Serial.println(buttonPressed);
}

void listenToButton(int slowPollingRate, int fastPollingRate) {
  if (!fastPolling) {
    if (millis() > buttonPollingTimerSlow + slowPollingRate) {
      buttonPollingTimerSlow = millis();
      digitalReadButton();
      if (buttonPressed) {
        fastPolling = true;
        pressCounter = 1;
      }
      else {
        buttonAction = NOACTION;
        pressCounter = 0;
      }
    }
  }
  else {
    if (millis() > buttonPollingTimerFast + fastPollingRate) {
      buttonPollingTimerFast = millis();
      Serial.println(interactionTimer);
      digitalReadButton();

      //count the time of pressing the button
      if (buttonPressed) {
        if (buttonReleased) {
          pressCounter++;
          buttonReleased = false;
          interactionTimer = 0;
        }
        interactionTimer += fastPollingRate;
      }
      else {
        buttonReleased = true;
      }

      //check type of interaction
      if (interactionTimer > timeLongPress) {
        buttonAction = LONGPRESSBUSY;
        if (!buttonPressed) {
          buttonReleased = false;
          fastPolling = false;
          interactionTimer = 0;
          pressCounter = 0;
          buttonAction = LONGPRESS;
        }
      }
      else if (interactionTimer > timeMediumPress) {
        buttonAction = MEDIUMPRESSBUSY;
        if (!buttonPressed) {
          buttonReleased = false;
          fastPolling = false;
          interactionTimer = 0;
          pressCounter = 0;
          buttonAction = MEDIUMPRESS;
        }
      }
```

```
      else if (interactionTimer > 0) {
        buttonAction = SHORTPRESSBUSY;
      }
      else {
        buttonAction = NOACTION;
      }

      //stop interaction if button is not being pressed and interactioTimeLimit is
    exceeded
      if (buttonReleased) {
        interactionTimer += fastPollingRate;
        if (interactionTimer > interactionTimeLimit) {
          buttonReleased = false;
          fastPolling = false;
          interactionTimer = 0;
          if (pressCounter <= 1) buttonAction = SHORTPRESS;
          else if (pressCounter == 2) buttonAction = DOUBLEPRESS;
          else  buttonAction = TRIPLEPRESS;
        }
      }
    }
  }
}
```

IMUFunctions.h

```
#include <Arduino_LSM6DSOX.h>


void intitIMU() {
  if (!IMU.begin()) {
    Serial.println("Failed to initialize IMU!");
  }

  Serial.print("Accelerometer sample rate = ");
  Serial.print(IMU.accelerationSampleRate());
  Serial.println(" Hz");
  Serial.println();
  Serial.println("Acceleration in g's");
  Serial.println("X\tY\tZ");
}

unsigned long prevMicros;
float IMUdata[] = {3, 3, 3, 3, 3, 3};
static float gyroAccelRatio = 0.999;
int accPitchOffset = 0;
float accPitch = 0;
float gyrPitch = 0;
float prevPitch = 0;
float pitch = 0;

void readIMU() {
  if (IMU.accelerationAvailable() && IMU.gyroscopeAvailable()) {
    IMU.readAcceleration(IMUdata[0], IMUdata[1], IMUdata[2]);
    IMU.readGyroscope(IMUdata[3], IMUdata[4], IMUdata[5]);
  }
}

void calculatePitchAngle() {
  int timeDelta = micros() - prevMicros;
  prevMicros = micros();
  prevPitch = accPitch;

  accPitch = atan2(IMUdata[1], sqrt(sq(IMUdata[2]) + sq(IMUdata[0]))) * 57.296;
```

```
  if (IMUdata[2] > 0) {
    gyrPitch = (pitch + IMUdata[3] * timeDelta / 1000 / 1000);
  }
  else if (IMUdata[2] < 0) {
    gyrPitch = (pitch - IMUdata[3] * timeDelta / 1000 / 1000);
  }
  pitch = gyroAccelRatio * gyrPitch + (1 - gyroAccelRatio) * accPitch;
}

int MAbuffer[200];
int MAindex = 0;
float calculateMovingAverage(float dataStream, int bufferSize) {
  MAbuffer[MAindex] = dataStream;

  float result;
  for (int i = 0; i < bufferSize; i++) {
    result += MAbuffer[i];
  }
  result = result / bufferSize;

  MAindex++;
  if (MAindex >= bufferSize){
    MAindex = 0;
  }
  return result;
}

String convertIMUtoString(float IMUdata[6]) {
  String output = String(millis());

  for (int i = 0; i < 7; i++) {
    if (i == 0) {
      output = String(output + ',' + IMUdata[i] + ',');
    }
    else if (i != 6) {
      output = String(output + IMUdata[i] + ',');
    }
    else {
      output = String(output + pitch);
    }
  }
  return output;
}
```

dataLoggingFunctions.h

```
#include <SPI.h>
#include <SD.h>

// set up variables using the SD utility library functions:
Sd2Card card;
SdVolume volume;
SdFile root;
//File root;
const int chipSelect = 10;
bool writingError = false;

void initSDcard() {
  Serial.print("Initializing SD card...");

  // see if the card is present and can be initialized:
  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    writingError = true;
```

```
  }
  else {
    Serial.println("card initialized.");
  }
}

String newWritableName = "senlog.csv";

void findNewFileName() {
  //Check if datalog file exists
  int logIndex = 0;
  char buffer[15];
  while (SD.exists(newWritableName)) {
//    if (logIndex < 10) {
//      newWritableName = String("datalog" + String(0) + String(logIndex) + ".csv");
//    } else {
//      newWritableName = String("datalog" + String(logIndex) + ".csv");
//    }
    sprintf(buffer, "senlog%d.csv", logIndex);
    newWritableName = buffer;
    logIndex++;
  }
  Serial.print("saving data to: ");
  Serial.println(newWritableName);
}

File dataFile;

void openNewSDFile() {
  // open the file. note that only one file can be open at a time,
  // so you have to close this one before opening another.
  dataFile = SD.open(newWritableName, FILE_WRITE);
}

void writeSDIMUlog(String dataString) {
  // if the file is available, write to it:
  if (dataFile) {
    dataFile.println(dataString);
    // print to the serial port too:
    if (Serial.available() > 0) {
      Serial.println(dataString);
    }
  }
  // if the file isn't open, pop up an error:
  else {
    Serial.print("error opening ");
    Serial.print(newWritableName);
    Serial.print(" and writing ");
    Serial.println(dataString);
    writingError = true;
  }
}

void closeSDlog() {
  dataFile.close();
}

void writeSDcalibrationValueLog(float calibrationValue) {
  dataFile = SD.open("LOG.csv", FILE_WRITE);
  String str = newWritableName + "," + millis() + "," + calibrationValue;
  dataFile.println(str);
  Serial.print("wrote \"");
  Serial.print(str);
```

```
  Serial.println("\" to the SDcard");
}
```

lightPatterns.h

```
byte redFadeToGreen[25][3] {
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {240, 16, 0},
  {224, 32, 0},
  {208, 48, 0},
  {192, 64, 0},
  {176, 80, 0},
  {160, 96, 0},
  {144, 112, 0},
  {128, 128, 0},
  {112, 144, 0},
  {96, 160, 0},
  {80, 176, 0},
  {64, 192, 0},
  {48, 208, 0},
  {32, 224, 0},
  {16, 240, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0}
};

byte greenFadeToRed[25][3] {
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {16, 240, 0},
  {32, 224, 0},
  {48, 208, 0},
  {64, 192, 0},
  {80, 176, 0},
  {96, 160, 0},
  {112, 144, 0},
  {128, 128, 0},
  {144, 112, 0},
  {160, 96, 0},
  {176, 80, 0},
  {192, 64, 0},
  {208, 48, 0},
  {224, 32, 0},
  {240, 16, 0},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
};
byte redRampUp[17][3] {
  {0, 0, 0},
  {16, 0, 0},
  {32, 0, 0},
```

```
  {48, 0, 0},
  {64, 0, 0},
  {80, 0, 0},
  {96, 0, 0},
  {112, 0, 0},
  {128, 0, 0},
  {144, 0, 0},
  {160, 0, 0},
  {176, 0, 0},
  {192, 0, 0},
  {208, 0, 0},
  {224, 0, 0},
  {240, 0, 0},
  {255, 0, 0}
};

byte redRampDown[17][3] {
  {255, 0, 0},
  {240, 0, 0},
  {224, 0, 0},
  {208, 0, 0},
  {192, 0, 0},
  {176, 0, 0},
  {160, 0, 0},
  {144, 0, 0},
  {128, 0, 0},
  {112, 0, 0},
  {96, 0, 0},
  {80, 0, 0},
  {64, 0, 0},
  {48, 0, 0},
  {32, 0, 0},
  {16, 0, 0},
  {0, 0, 0}
};

byte greenRampUp[17][3] {
  {30, 0, 0},
  {30, 16, 0},
  {30, 32, 0},
  {30, 48, 0},
  {30, 64, 0},
  {30, 80, 0},
  {30, 96, 0},
  {30, 112, 0},
  {30, 128, 0},
  {30, 144, 0},
  {30, 160, 0},
  {30, 176, 0},
  {30, 192, 0},
  {30, 208, 0},
  {30, 224, 0},
  {30, 240, 0},
  {30, 255, 0}
};

byte greenRampDown[17][3] {
  {30, 255, 0},
  {30, 240, 0},
  {30, 224, 0},
  {30, 208, 0},
  {30, 192, 0},
  {30, 176, 0},
```

```
  {30, 160, 0},
  {30, 144, 0},
  {30, 128, 0},
  {30, 112, 0},
  {30, 96, 0},
  {30, 80, 0},
  {30, 64, 0},
  {30, 48, 0},
  {30, 32, 0},
  {30, 16, 0},
  {30, 0, 0}
};

byte blueFadeInOut[36][3] = {
  {0, 0, 0},
  {0, 0, 26} ,
  {0, 0, 51} ,
  {0, 0, 77} ,
  {0, 0, 102} ,
  {0, 0, 128} ,
  {0, 0, 153} ,
  {0, 0, 179} ,
  {0, 0, 204} ,
  {0, 0, 230} ,
  {0, 0, 255},
  {0, 0, 255} ,
  {0, 0, 255} ,
  {0, 0, 255} ,
  {0, 0, 255} ,
  {0, 0, 255} ,
  {0, 0, 255} ,
  {0, 0, 255} ,
  {0, 0, 230} ,
  {0, 0, 204} ,
  {0, 0, 179} ,
  {0, 0, 153} ,
  {0, 0, 128} ,
  {0, 0, 102},
  {0, 0, 77} ,
  {0, 0, 51} ,
  {0, 0, 26} ,
  {0, 0, 20} ,
  {0, 0, 15} ,
  {0, 0, 10} ,
  {0, 0, 8} ,
  {0, 0, 6} ,
  {0, 0, 4} ,
  {0, 0, 3} ,
  {0, 0, 2} ,
  {0, 0, 1}
};

byte greenFadeInOut[36][3] = {
  {0, 0, 0},
  {0, 26, 0} ,
  {0, 51, 0} ,
  {0, 77, 0} ,
  {0, 102, 0} ,
  {0, 128, 0} ,
  {0, 153, 0} ,
  {0, 179, 0} ,
  {0, 204, 0} ,
  {0, 230, 0} ,
```

```
  {0, 255, 0},
  {0, 255, 0} ,
  {0, 255, 0} ,
  {0, 255, 0} ,
  {0, 255, 0} ,
  {0, 255, 0} ,
  {0, 255, 0} ,
  {0, 255, 0} ,
  {0, 230, 0} ,
  {0, 204, 0} ,
  {0, 179, 0} ,
  {0, 153, 0} ,
  {0, 128, 0} ,
  {0, 102, 0},
  {0, 77, 0} ,
  {0, 51, 0} ,
  {0, 26, 0} ,
  {0, 20, 0} ,
  {0, 15, 0} ,
  {0, 10, 0} ,
  {0, 8, 0} ,
  {0, 6, 0} ,
  {0, 4, 0} ,
  {0, 3, 0} ,
  {0, 2, 0} ,
  {0, 1, 0}
};

byte redFadeInOut[36][3] = {
  {0, 0, 0},
  {26, 0, 0} ,
  {51, 0, 0} ,
  {77, 0, 0} ,
  {102, 0, 0} ,
  {128, 0, 0} ,
  {153, 0, 0} ,
  {179, 0, 0} ,
  {204, 0, 0} ,
  {230, 0, 0} ,
  {255, 0, 0},
  {255, 0, 0} ,
  {255, 0, 0} ,
  {255, 0, 0} ,
  {255, 0, 0} ,
  {255, 0, 0} ,
  {255, 0, 0} ,
  {255, 0, 0} ,
  {230, 0, 0} ,
  {204, 0, 0} ,
  {179, 0, 0} ,
  {153, 0, 0} ,
  {128, 0, 0} ,
  {102, 0, 0},
  {77, 0, 0} ,
  {51, 0, 0} ,
  {26, 0, 0} ,
  {20, 0, 0} ,
  {15, 0, 0} ,
  {10, 0, 0} ,
  {8, 0, 0} ,
  {6, 0, 0} ,
  {4, 0, 0} ,
  {3, 0, 0} ,
```

```
  {2, 0, 0} ,
  {1, 0, 0}
};

byte yellowFadeInOut[36][3] = {
  {0, 0, 0},
  {26, 26, 0} ,
  {51, 51, 0} ,
  {77, 77, 0} ,
  {102, 102, 0} ,
  {128, 128, 0} ,
  {153, 153, 0} ,
  {179, 179, 0} ,
  {204, 204, 0} ,
  {230, 230, 0} ,
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {230, 230, 0} ,
  {204, 204, 0} ,
  {179, 179, 0} ,
  {153, 153, 0} ,
  {128, 128, 0} ,
  {102, 102, 0},
  {77, 77, 0} ,
  {51, 51, 0} ,
  {26, 26, 0} ,
  {20, 20, 0} ,
  {15, 15, 0} ,
  {10, 10, 0} ,
  {8, 8, 0} ,
  {6, 6, 0} ,
  {4, 4, 0} ,
  {3, 3, 0} ,
  {2, 2, 0} ,
  {1, 1, 0}
};

byte yellowThreeFlashes[8][3] {
  {0, 0, 0},
  {255, 255, 0},
  {0, 0, 0},
  {255, 255, 0},
  {0, 0, 0},
  {255, 255, 0},
  {0, 0, 0},
  {0, 0, 0}
};

byte redThreeFlashes[8][3] {
  {0, 0, 0},
  {255, 0, 0},
  {0, 0, 0},
  {255, 0, 0},
  {0, 0, 0},
  {255, 0, 0},
  {0, 0, 0},
  {0, 0, 0}
```

```
};

byte blueThreeFlashes[8][3] {
  {0, 0, 0},
  {0, 0, 255},
  {0, 0, 0},
  {0, 0, 255},
  {0, 0, 0},
  {0, 0, 255},
  {0, 0, 0},
  {0, 0, 0}
};

byte rainbowFlash[14][3] {
  {255, 0, 0},
  {0, 0, 0},
  {255, 127, 0},
  {0, 0, 0},
  {255, 255, 0},
  {0, 0, 0},
  {0, 255, 0},
  {0, 0, 0},
  {0, 0, 255},
  {0, 0, 0},
  {75, 0, 130},
  {0, 0, 0},
  {148, 0, 211},
  {0, 0, 0}
};
byte rainbowGradient[24][3] {
  {255, 0, 0},
  {255, 64, 0},
  {255, 127, 0},
  {255, 192, 0},
  {255, 255, 0},
  {192, 255, 0},
  {127, 255, 0},
  {64, 255, 0},
  {0, 255, 0},
  {0, 255, 64},
  {0, 255, 127},
  {0, 255, 192},
  {0, 255, 255},
  {0, 192, 255},
  {0, 127, 255},
  {0, 64, 255},
  {0, 0, 255},
  {64, 0, 255},
  {127, 0, 255},
  {192, 0, 255},
  {255, 0, 255},
  {255, 0, 192},
  {255, 0, 127},
  {255, 0, 64}
};

byte greenToBlueAndBack[30][3] {
  {0, 255, 0},
  {0, 230, 26} ,
  {0, 204, 51} ,
  {0, 179, 77} ,
  {0, 153, 102} ,
  {0, 128, 128} ,
```

```
  {0, 102, 153} ,
  {0, 77, 179} ,
  {0, 51, 204} ,
  {0, 26, 230} ,
  {0, 0, 255},
  {0, 0, 255},
  {0, 0, 255},
  {0, 0, 255},
  {0, 0, 255},
  {0, 0, 255},
  {0, 26, 230} ,
  {0, 51, 204} ,
  {0, 77, 179} ,
  {0, 102, 153} ,
  {0, 128, 128} ,
  {0, 153, 102} ,
  {0, 179, 77} ,
  {0, 204, 51} ,
  {0, 230, 26} ,
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0}
};

byte blueToGreenTwoBlip[24][3] {
  {0, 0, 255},
  {0, 0, 255},
  {0, 26, 230} ,
  {0, 51, 204} ,
  {0, 77, 179} ,
  {0, 102, 153} ,
  {0, 128, 128} ,
  {0, 153, 102} ,
  {0, 179, 77} ,
  {0, 204, 51} ,
  {0, 230, 26} ,
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 0, 0},
  {0, 0, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 0, 0},
  {0, 0, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 0, 0},
  {0, 0, 0}
};

byte blueToRedTwoBlip[24][3] {
  {0, 0, 255},
  {0, 0, 255},
  {26, 0, 230} ,
  {51, 0, 204} ,
  {77, 0, 179} ,
  {102, 0, 153} ,
  {128, 0, 128} ,
  {153, 0, 102} ,
  {179, 0, 77} ,
```

```
  {204, 0, 51} ,
  {230, 0, 26} ,
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {0, 0, 0},
  {0, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {0, 0, 0},
  {0, 0, 0},
  {255, 0, 0},
  {255, 0, 0},
  {0, 0, 0},
  {0, 0, 0}
};

byte blueWithRedI[5][3] {
  {0, 0, 255},
  {0, 0, 255},
  {0, 0, 255},
  {0, 0, 255},
  {40, 0, 0}
};
byte blueWithRedII[5][3] {
  {0, 0, 255},
  {0, 0, 255},
  {0, 0, 255},
  {150, 0, 0},
  {150, 0, 0}
};
byte blueWithRedIII[5][3] {
  {0, 0, 255},
  {0, 0, 255},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0}
};

byte greenWithRedI[5][3] {
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {40, 0, 0}
};
byte greenWithRedII[5][3] {
  {0, 255, 0},
  {0, 255, 0},
  {0, 255, 0},
  {150, 0, 0},
  {150, 0, 0}
};
byte greenWithRedIII[5][3] {
  {0, 255, 0},
  {0, 255, 0},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0}
};

byte yellowWithRedI[5][3] {
  {255, 255, 0},
```

```
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {40, 0, 0}
};
byte yellowWithRedII[5][3] {
  {255, 255, 0},
  {255, 255, 0},
  {255, 255, 0},
  {150, 0, 0},
  {150, 0, 0}
};
byte yellowWithRedIII[5][3] {
  {255, 255, 0},
  {255, 255, 0},
  {255, 0, 0},
  {255, 0, 0},
  {255, 0, 0}
}
```

C RPLOTS

C.0.1 Backstroke per lane

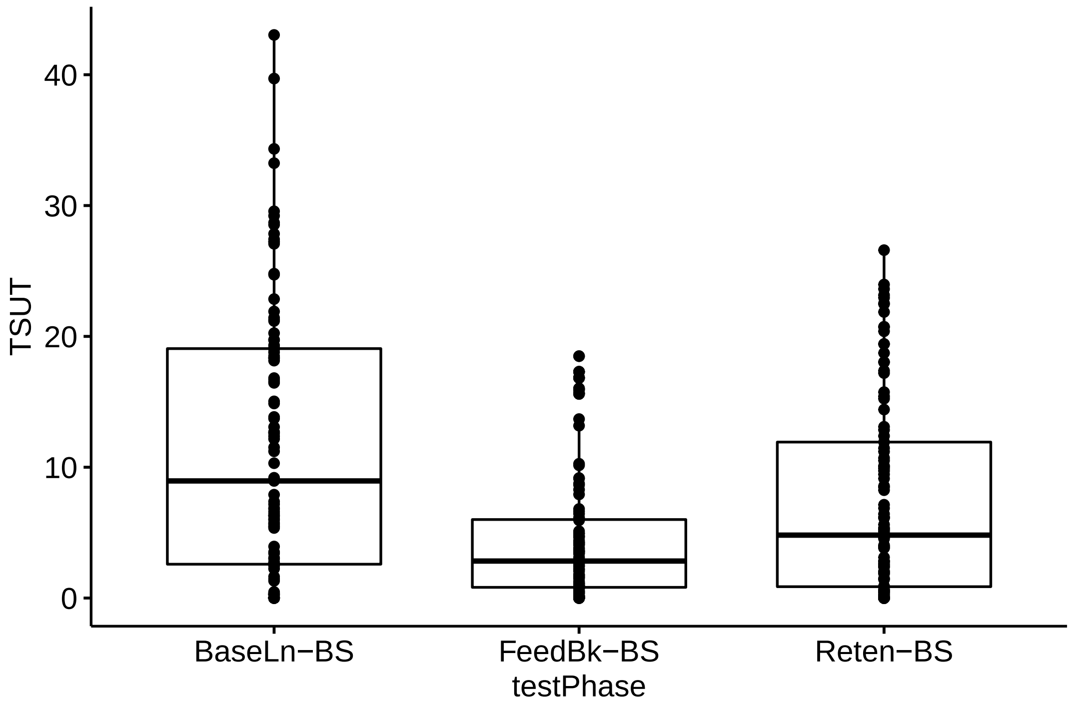

Figure C.1: A box plot which depicts the overall time spend under threshold (TSUT) per lane for all lanes swum in backstroke in the three different test phases.

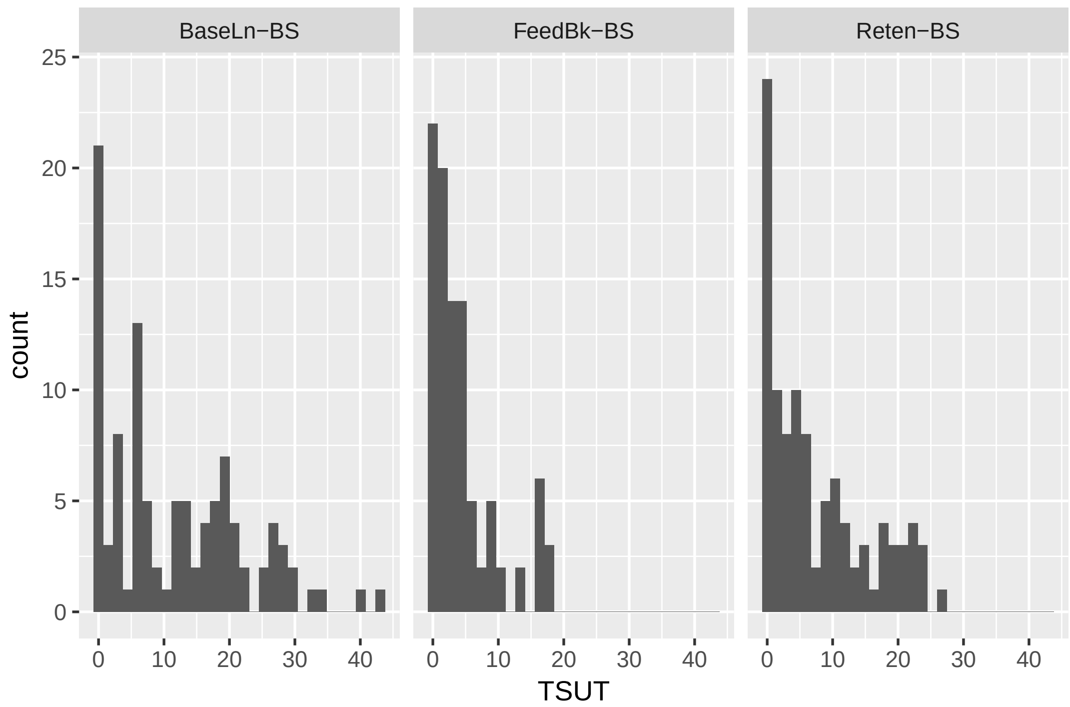

Figure C.2: A histogram which depicts the overall time spend under threshold (TSUT) per lane for all lanes swum in backstroke in the three different test phases.

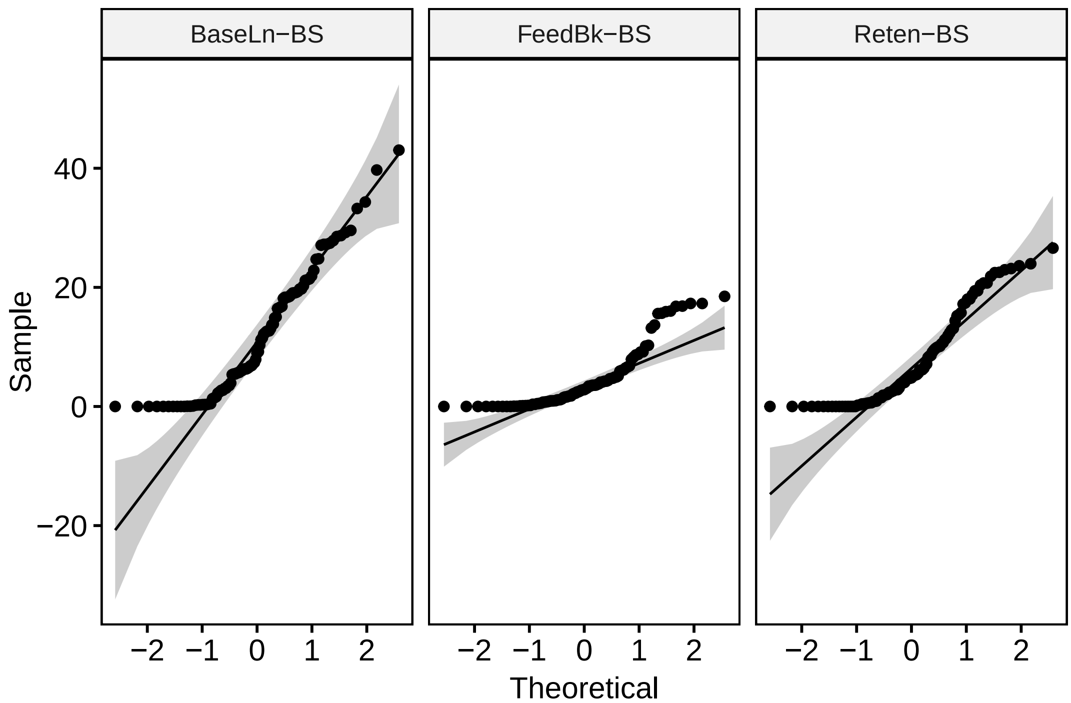

Figure C.3: A QQ plot which depicts the overall time spend under threshold (TSUT) per lane for all lanes swum in backstroke in the three different test phases.

C.0.2 Backstroke per lane transformed

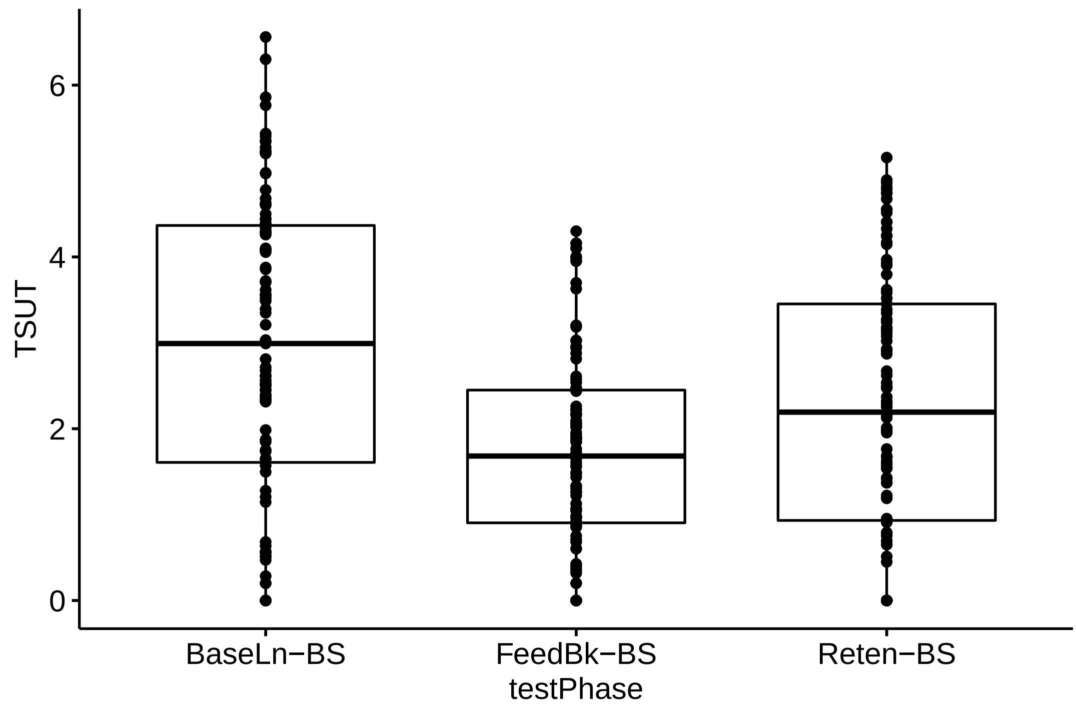

Figure C.4: A box plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane for all lanes swum in backstroke in the three different test phases.

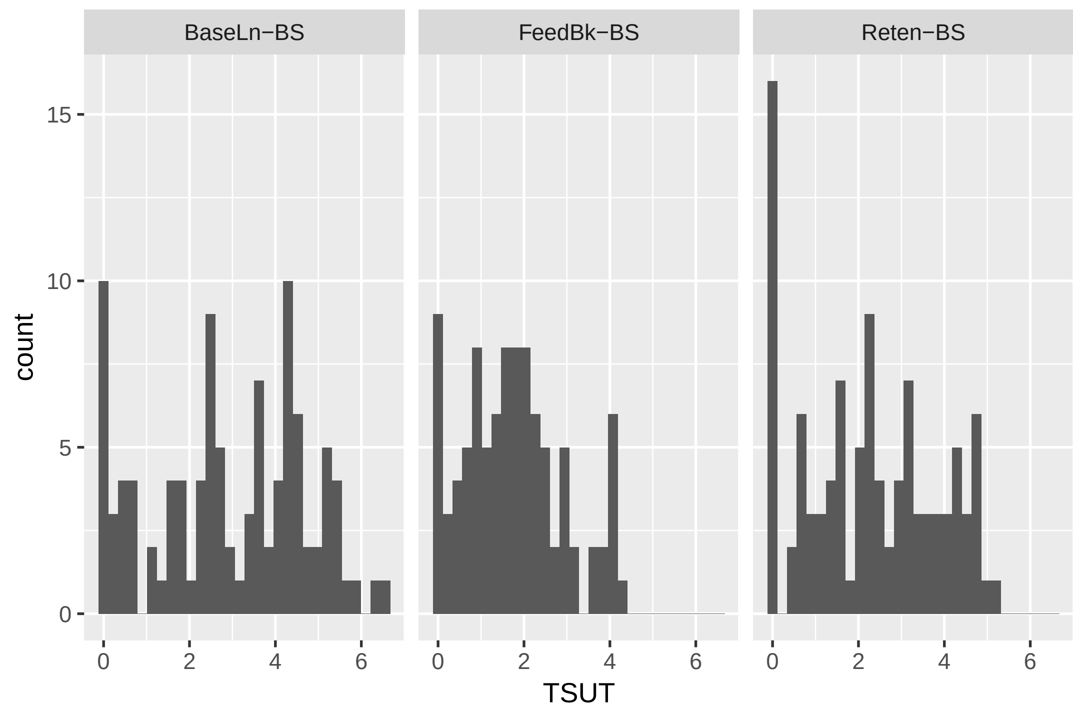

Figure C.5: A histogram which depicts the root-transformed overall time spend under threshold (TSUT) per lane for all lanes swum in backstroke in the three different test phases.

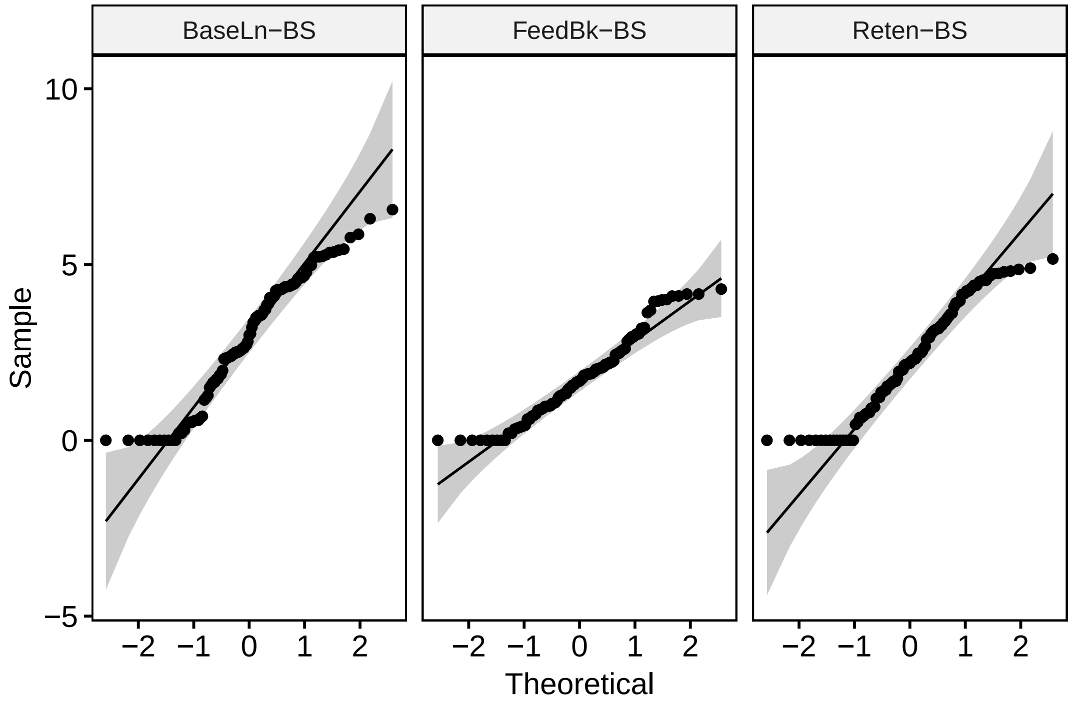

Figure C.6: A QQ plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane for all lanes swum in backstroke in the three different test phases.

C.0.3 Backstroke per testphase

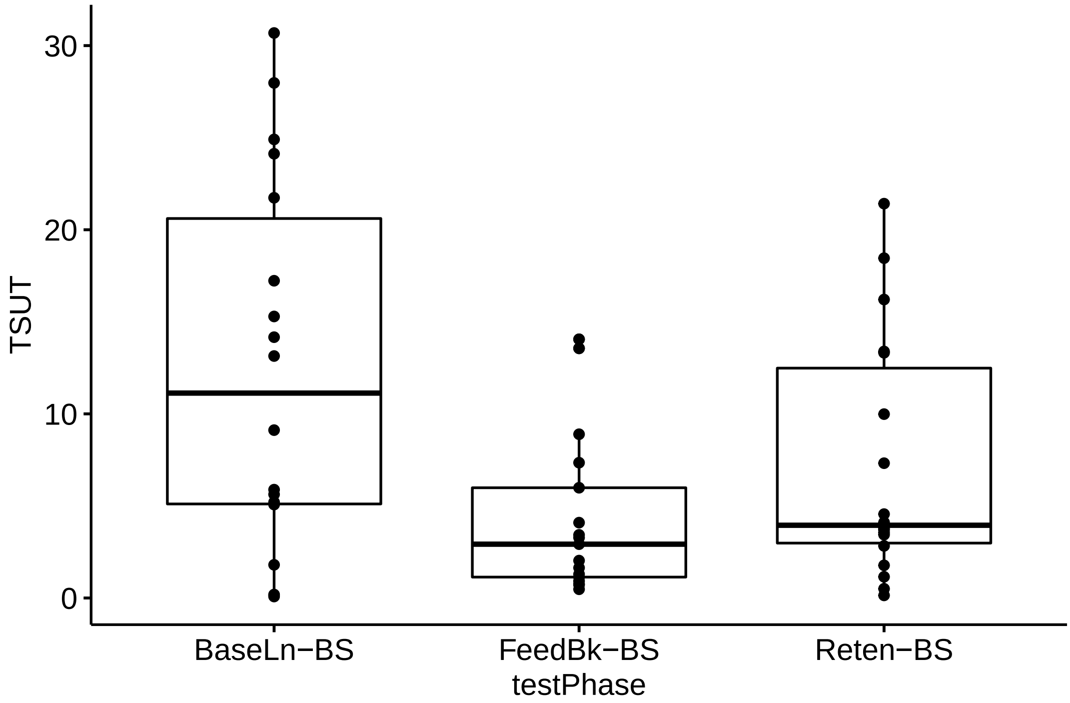

Figure C.7: A box plot which depicts the average time spend under threshold (TSUT) per lane in backstroke for the three different test phases.

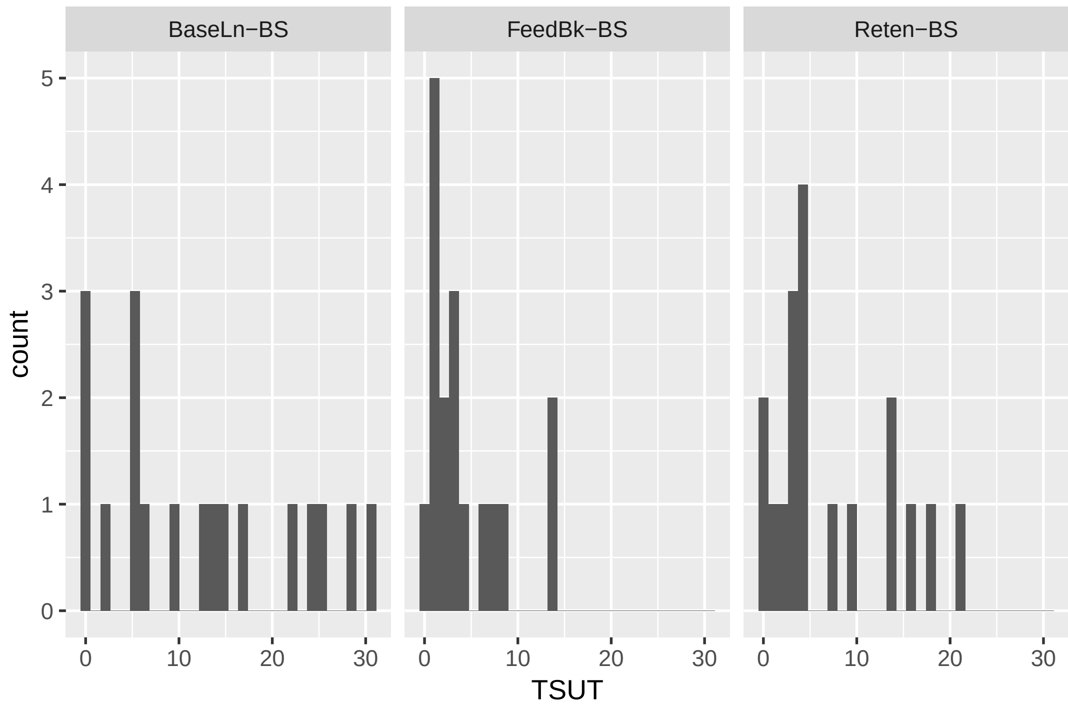

Figure C.8: A histogram which depicts the overall time spend under threshold (TSUT) per lane in backstroke for the three different test phases.

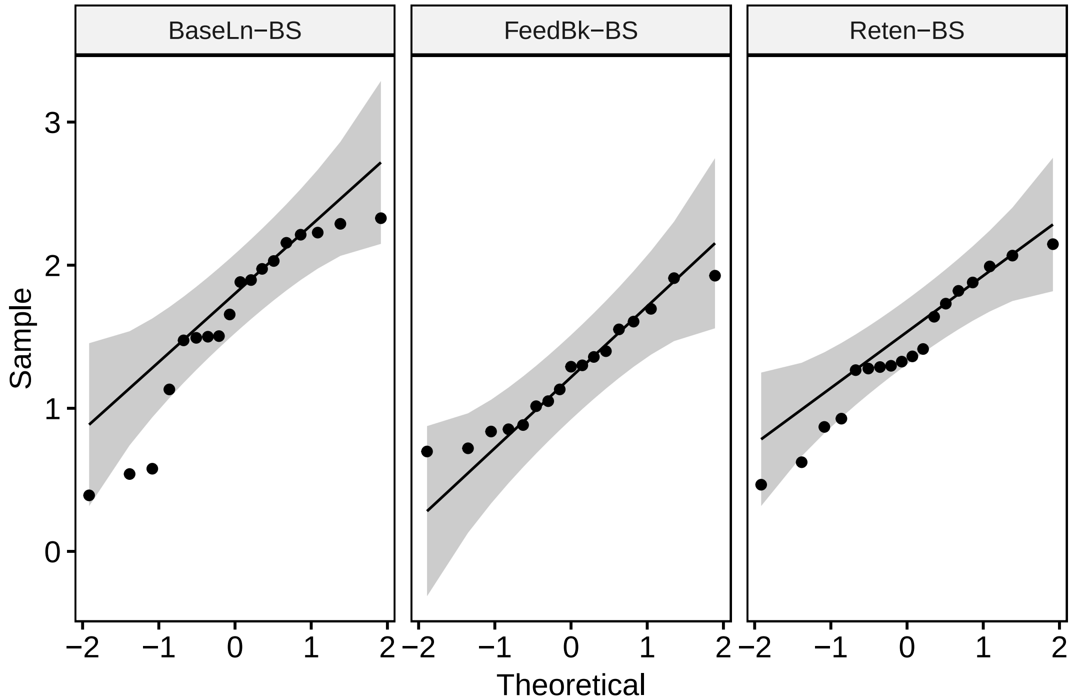

Figure C.9: A QQ plot which depicts the overall time spend under threshold (TSUT) per lane in backstroke for the three different test phases.

C.0.4 Backstroke per testphase transformed

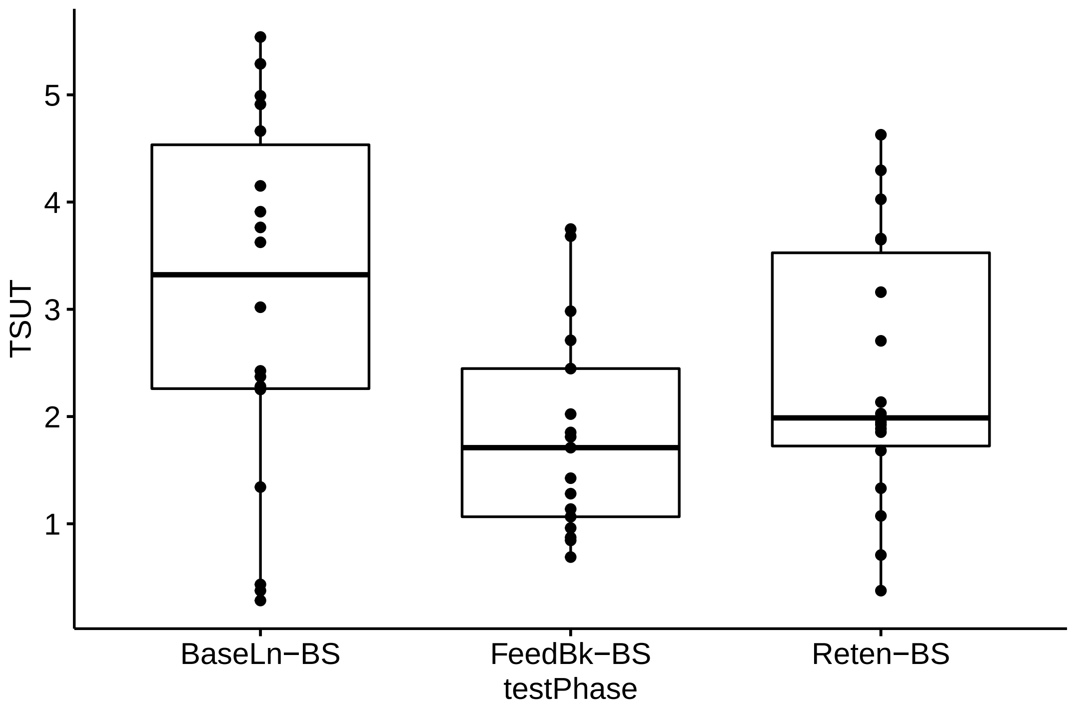

Figure C.10: A box plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane in backstroke for the three different test phases.

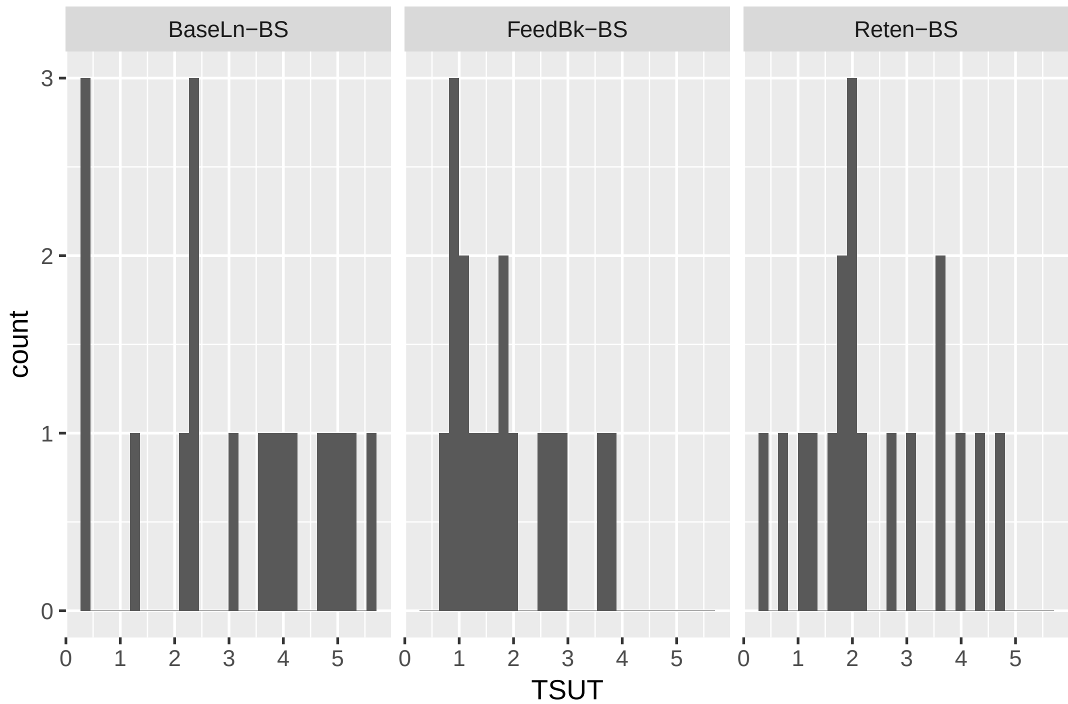

Figure C.11: A histogram which depicts the root-transformed overall time spend under threshold (TSUT) per lane swum in backstroke for the three different test phases.

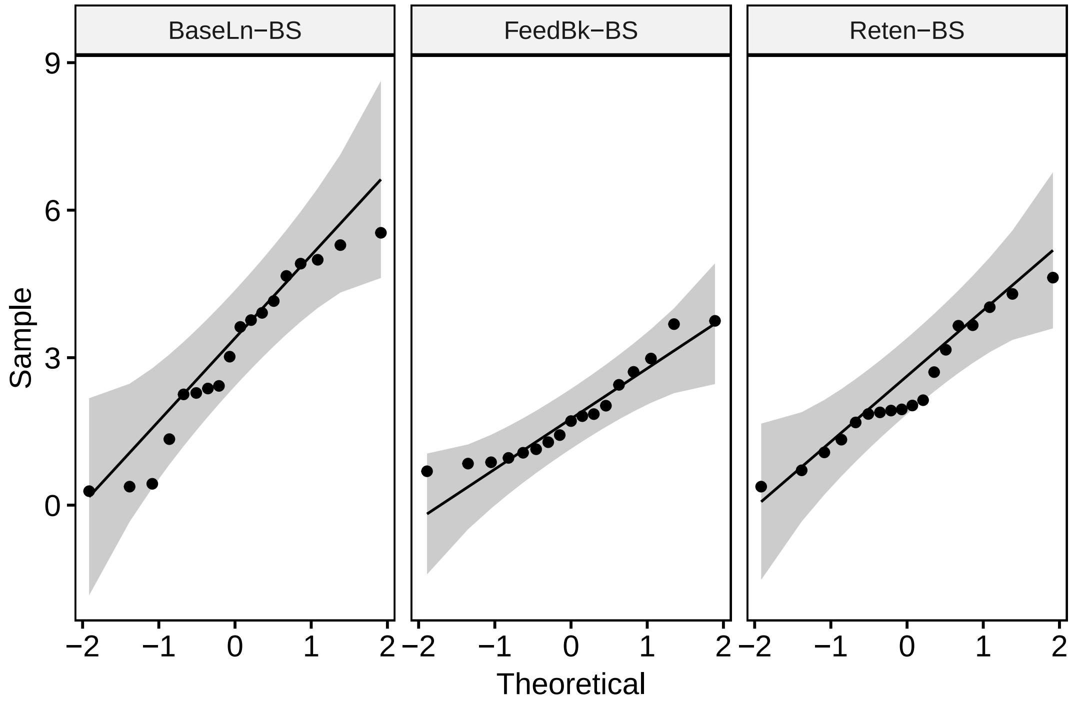

Figure C.12: A QQ plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane swum in backstroke for the three different test phases.

C.0.5 Freestyle per lane

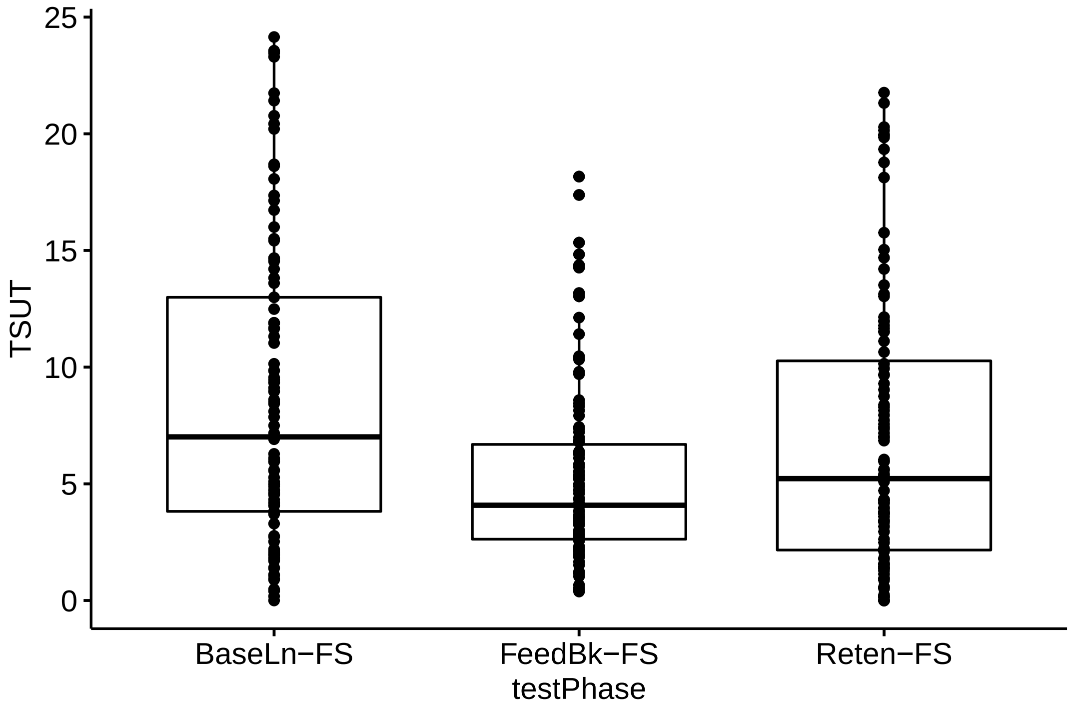

Figure C.13: A box plot which depicts the overall time spend under threshold (TSUT) per lane for all lanes swum in freestyle in the three different test phases.

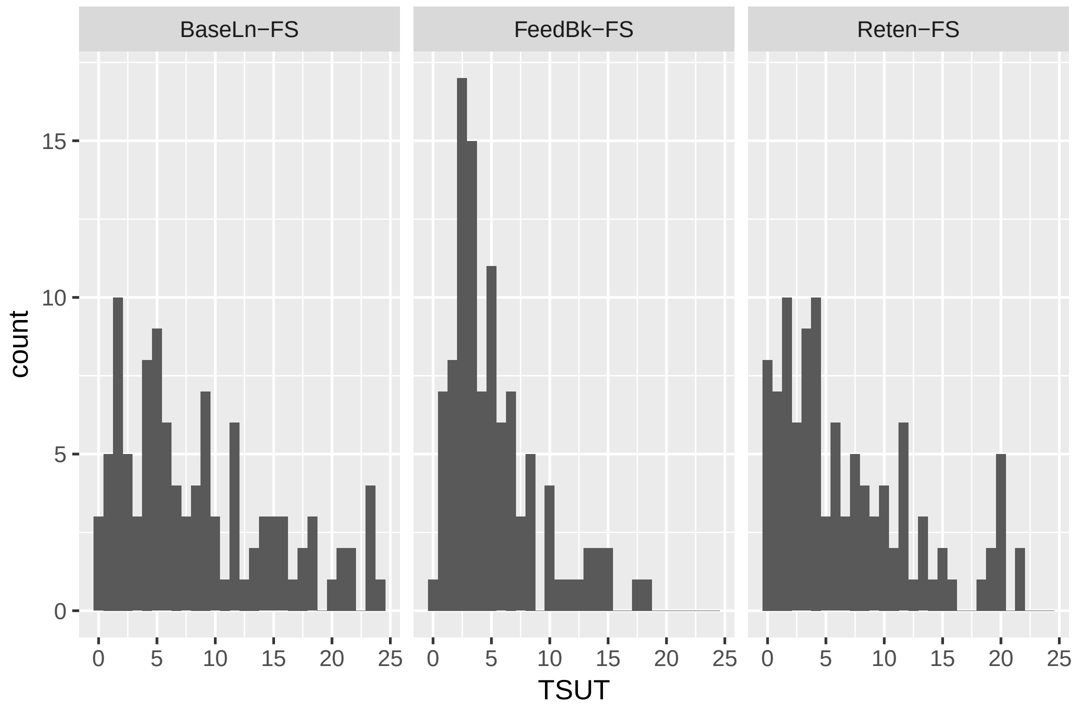

Figure C.14: A histogram which depicts the overall time spend under threshold (TSUT) per lane for all lanes swum in freestyle in the three different test phases.

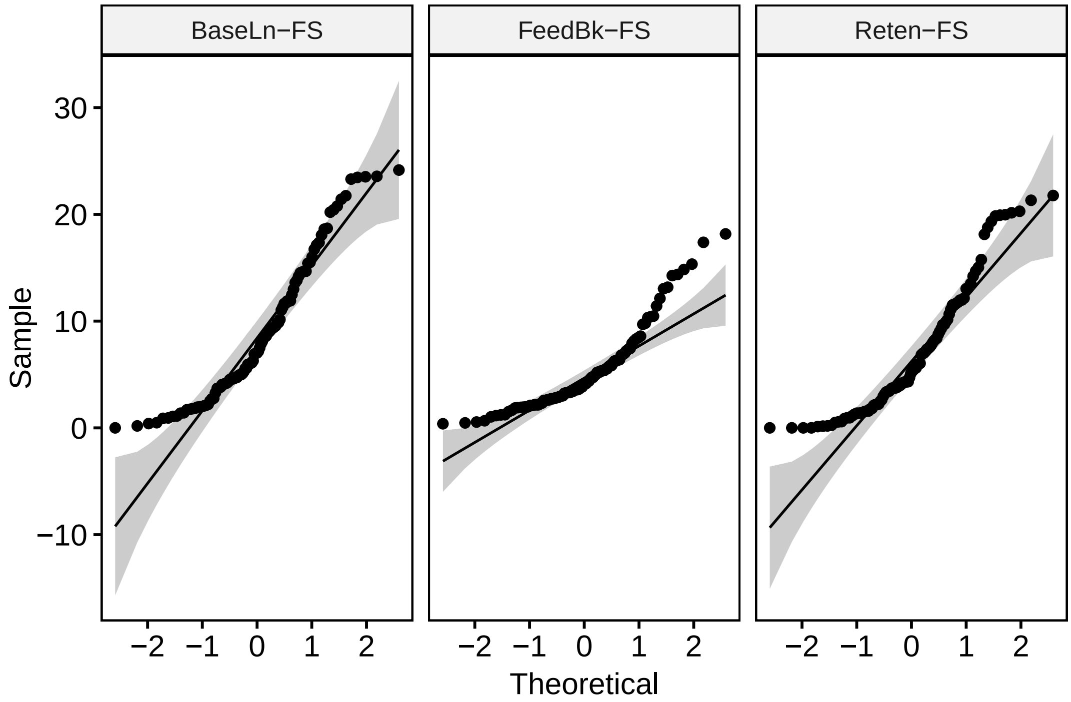

Figure C.15: A QQ plot which depicts the overall time spend under threshold (TSUT) per lane for all lanes swum in freestyle in the three different test phases.

C.0.6 Freestyle per lane transformed

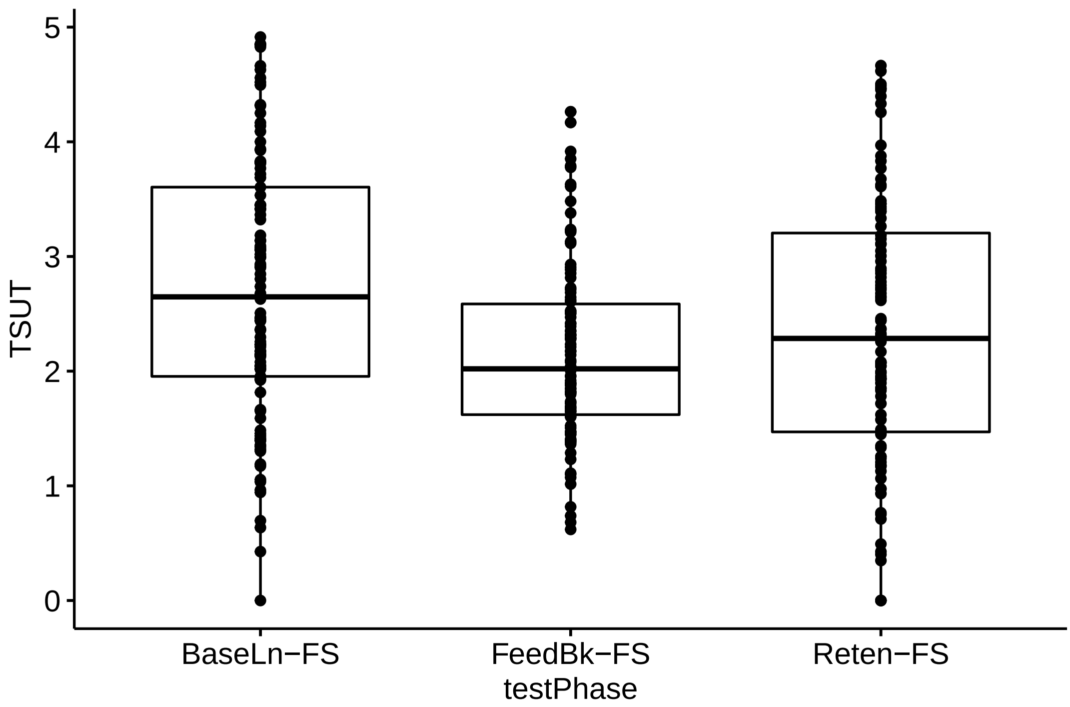

Figure C.16: A box plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane for all lanes swum in freestyle in the three different test phases.

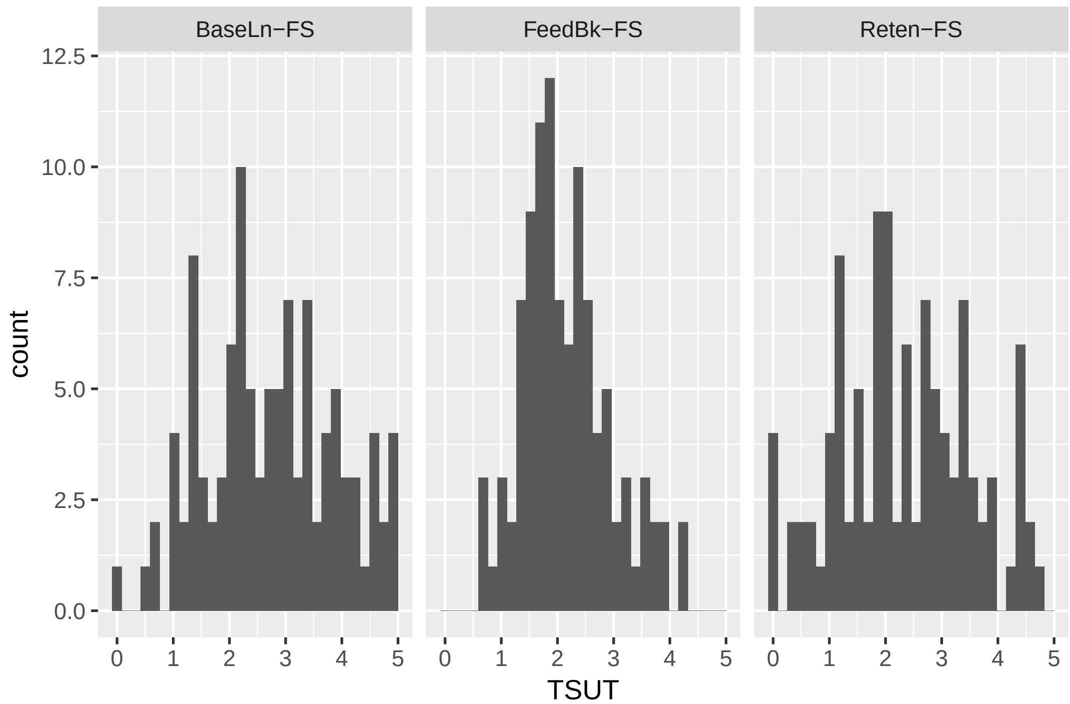

Figure C.17: A histogram which depicts the root-transformed overall time spend under threshold (TSUT) per lane for all lanes swum in freestyle in the three different test phases.

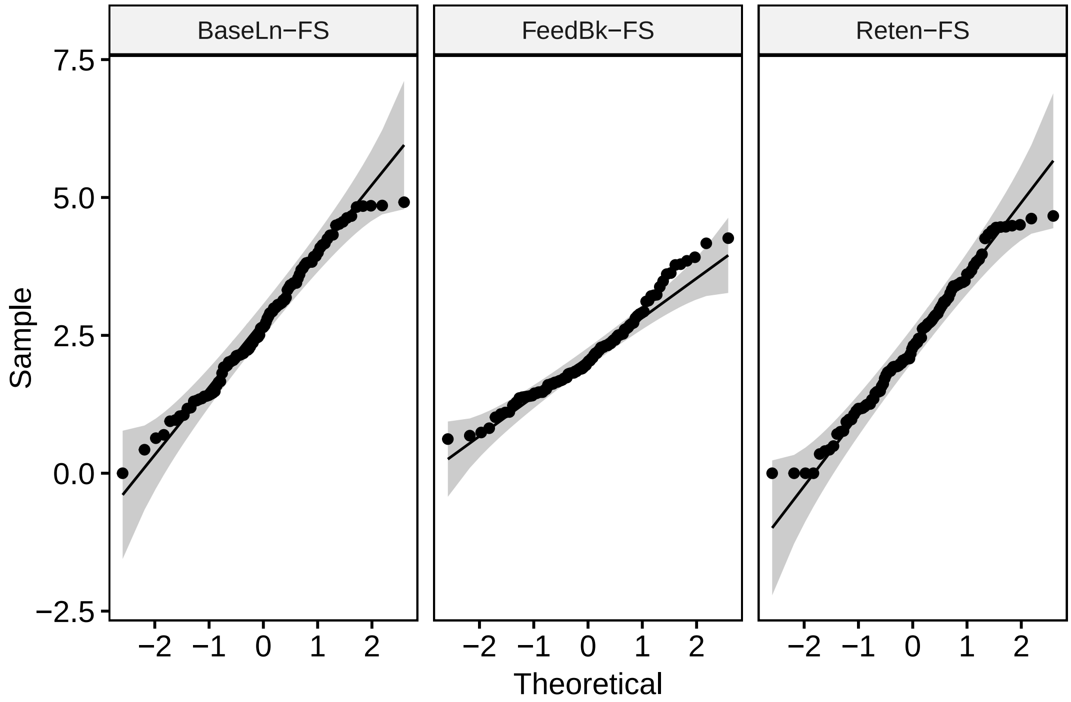

Figure C.18: A QQ plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane for all lanes swum in freestyle in the three different test phases.

C.0.7 Freestyle per phase

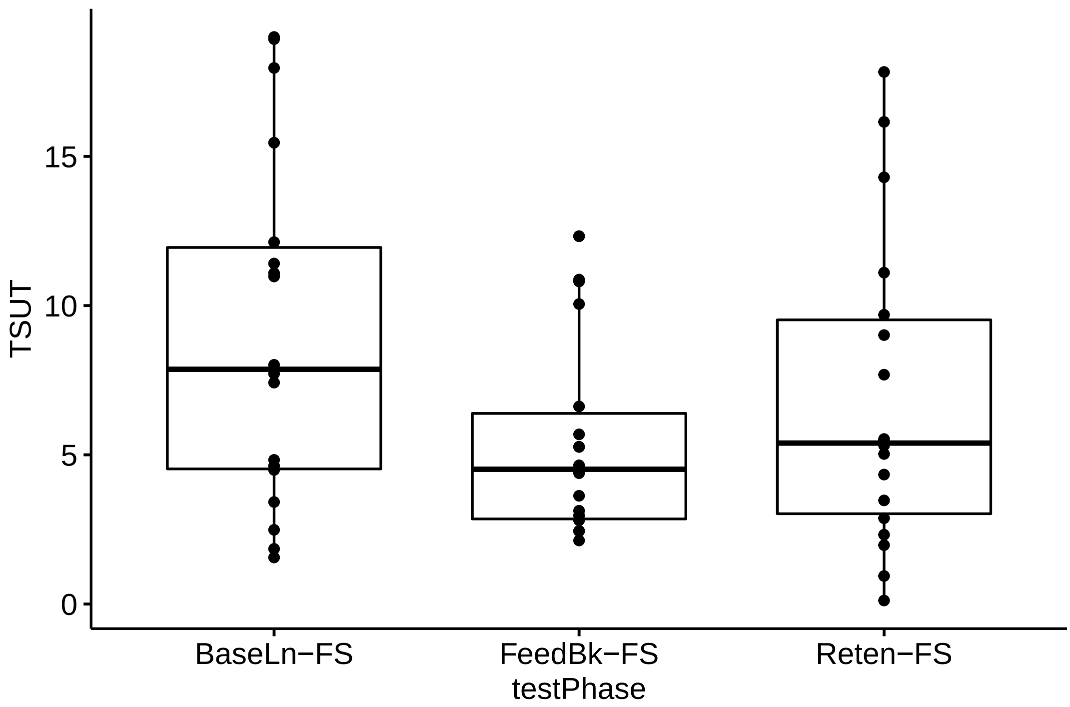

Figure C.19: A box plot which depicts the average time spend under threshold (TSUT) per lane in freestyle for the three different test phases.

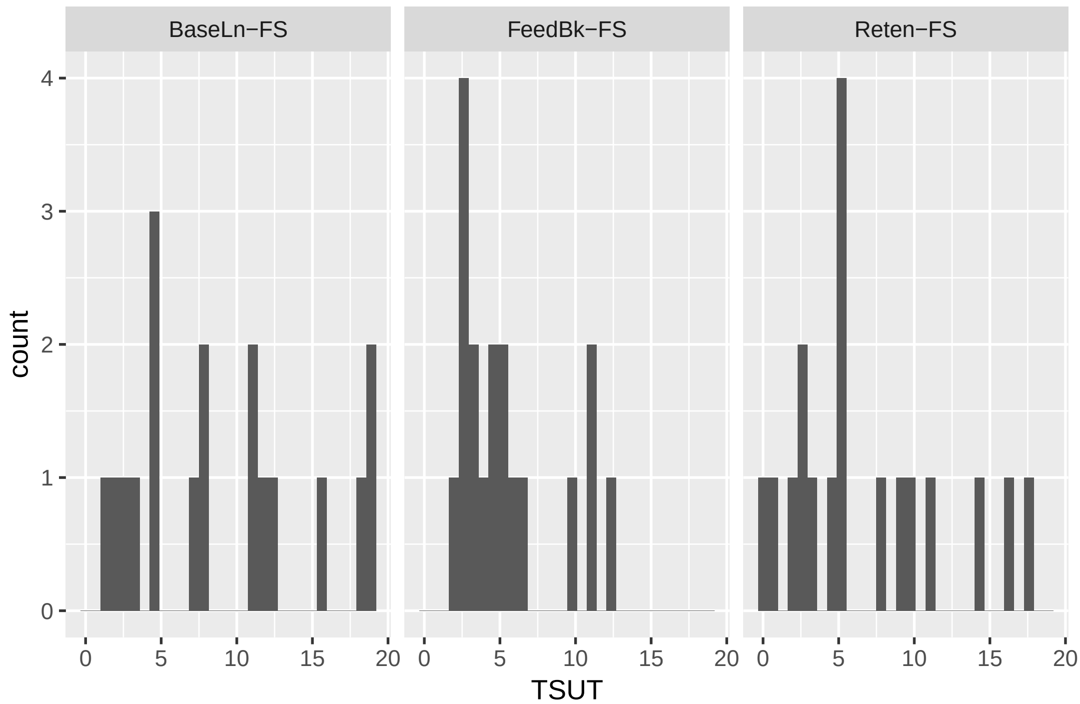

Figure C.20: A histogram which depicts the overall time spend under threshold (TSUT) per lane in freestyle for the three different test phases.

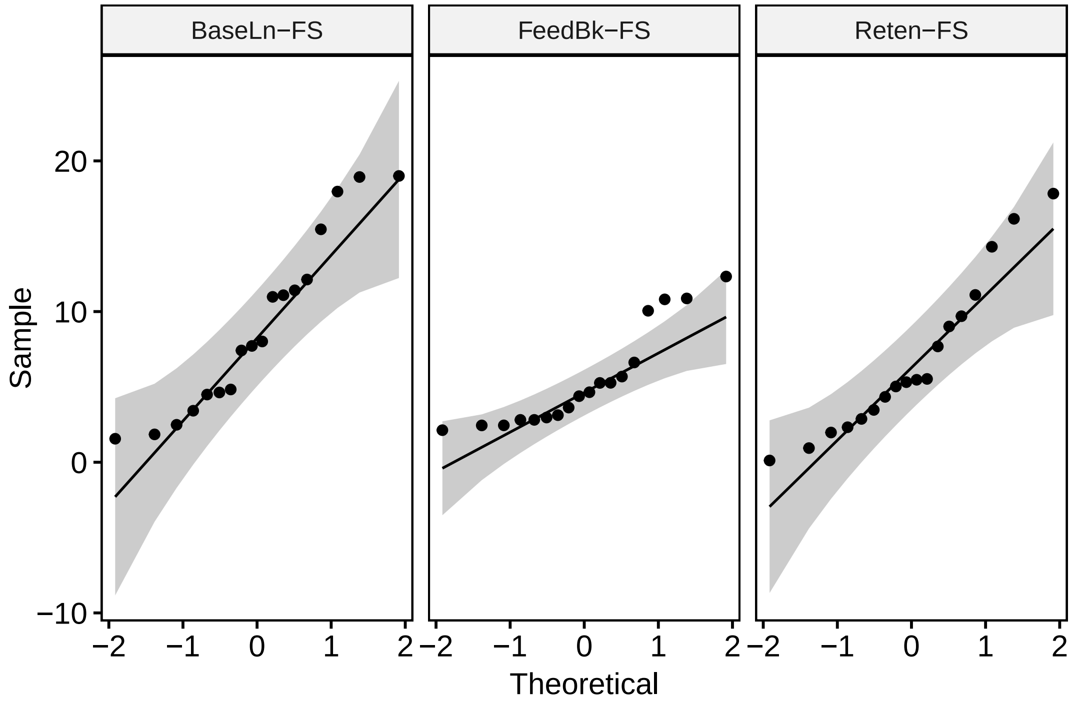

Figure C.21: A QQ plot which depicts the overall time spend under threshold (TSUT) per lane in freestyle for the three different test phases.

C.0.8 Freestyle per phase transformed

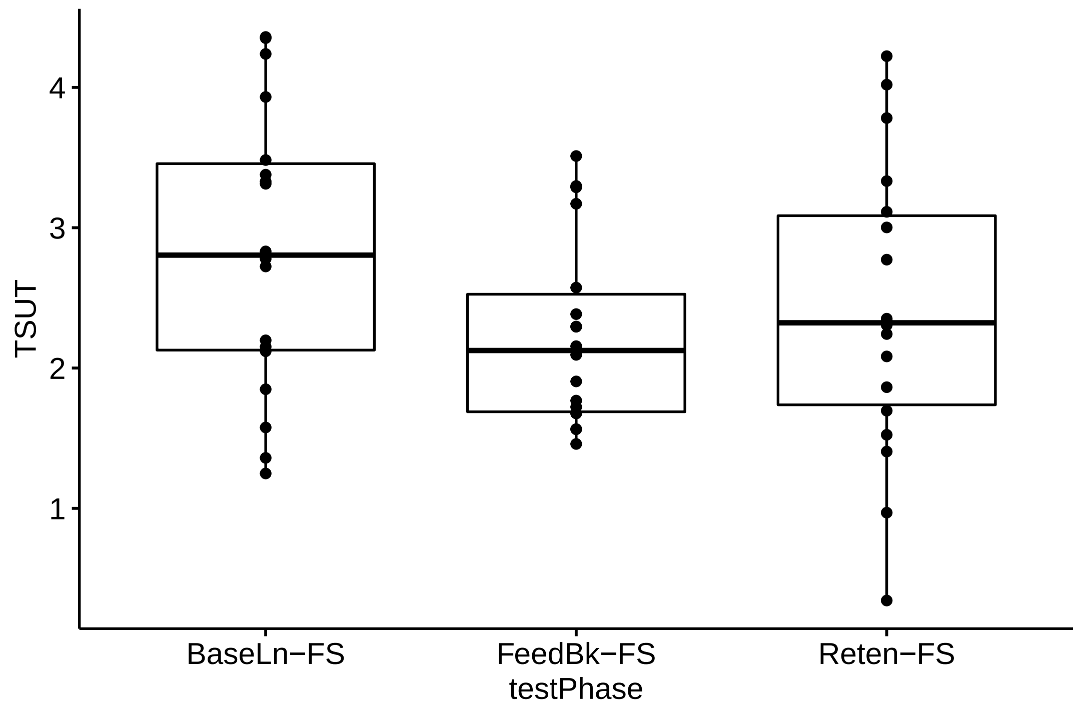

Figure C.22: A box plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane in freestyle for the three different test phases.

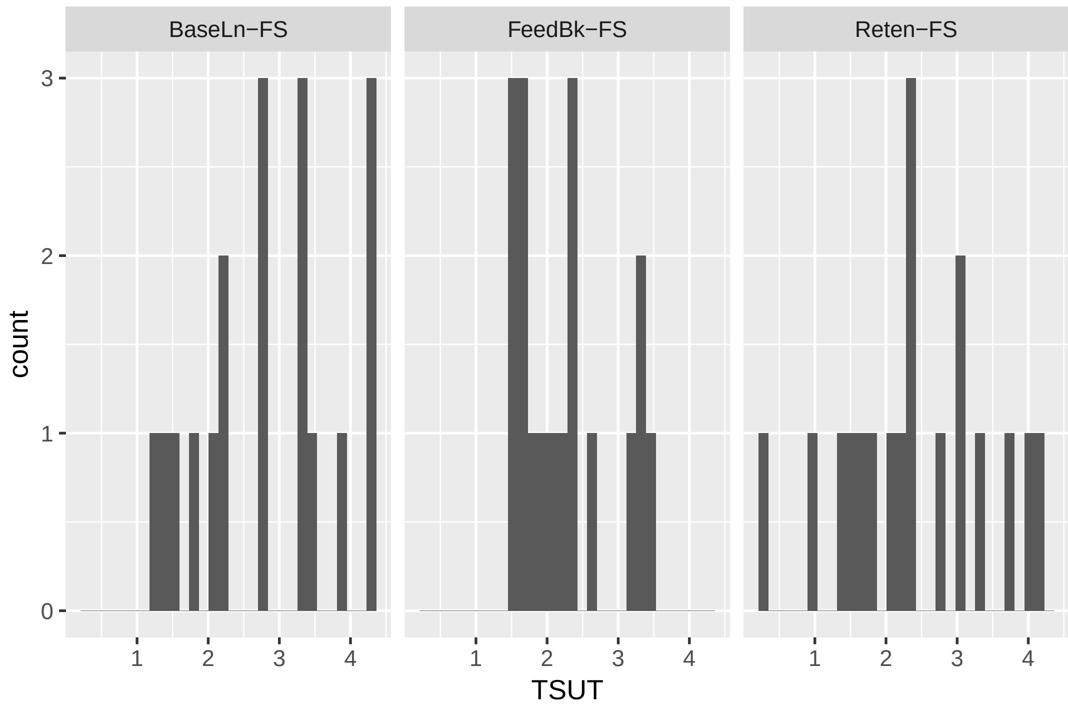

Figure C.23: A histogram which depicts the root-transformed overall time spend under threshold (TSUT) per lane swum in freestyle for the three different test phases.

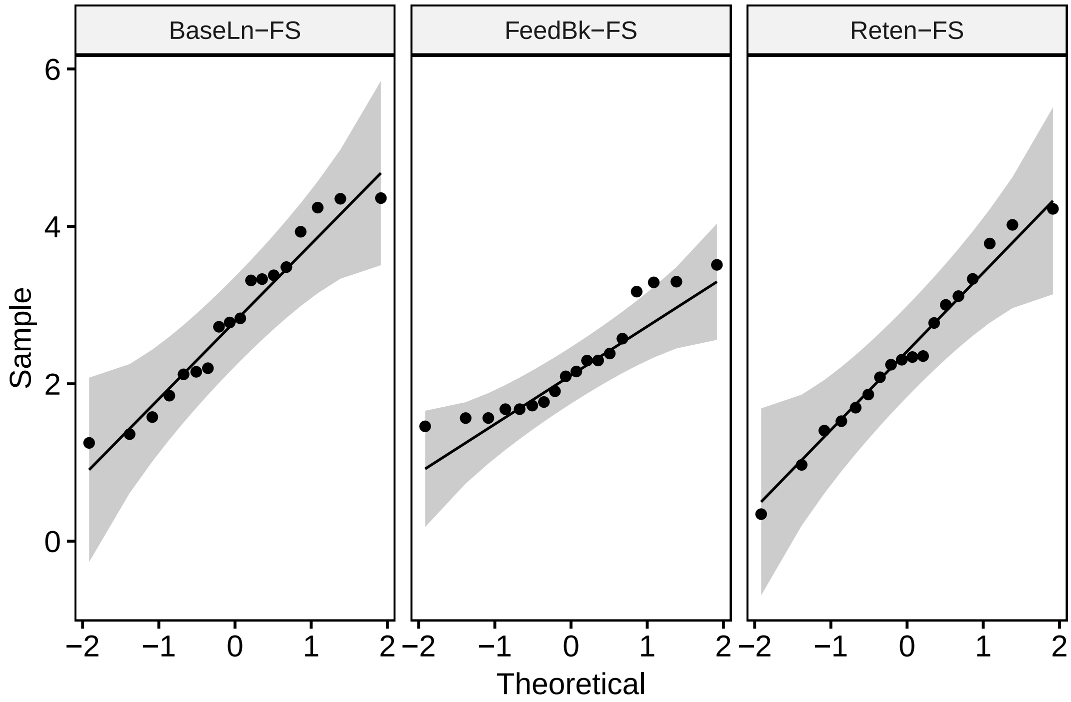

Figure C.24: A QQ plot which depicts the root-transformed overall time spend under threshold (TSUT) per lane swum in freestyle for the three different test phases.

D TEST SUMMARIES

D.1 Test P1 Summary

D.1.1 FreeStyle Body Balance

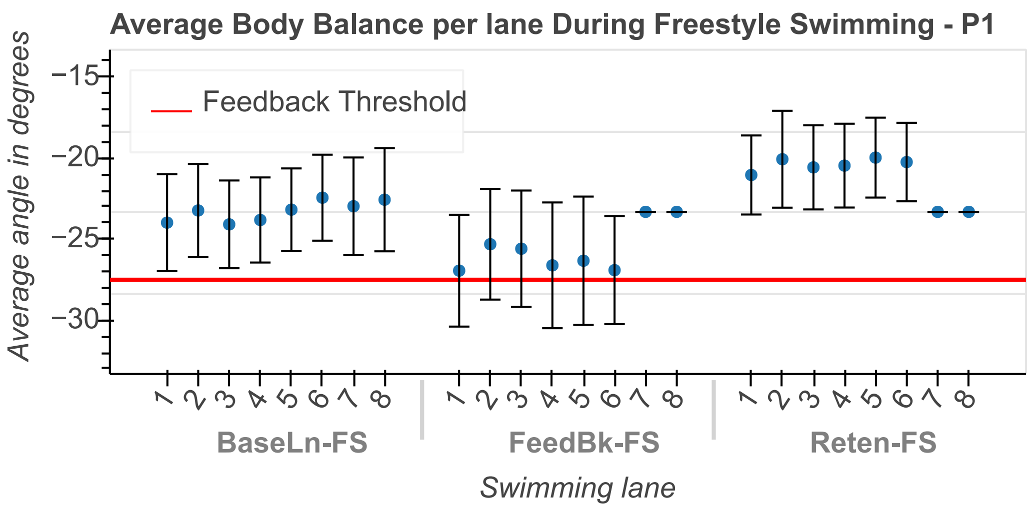

Figure D.1: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

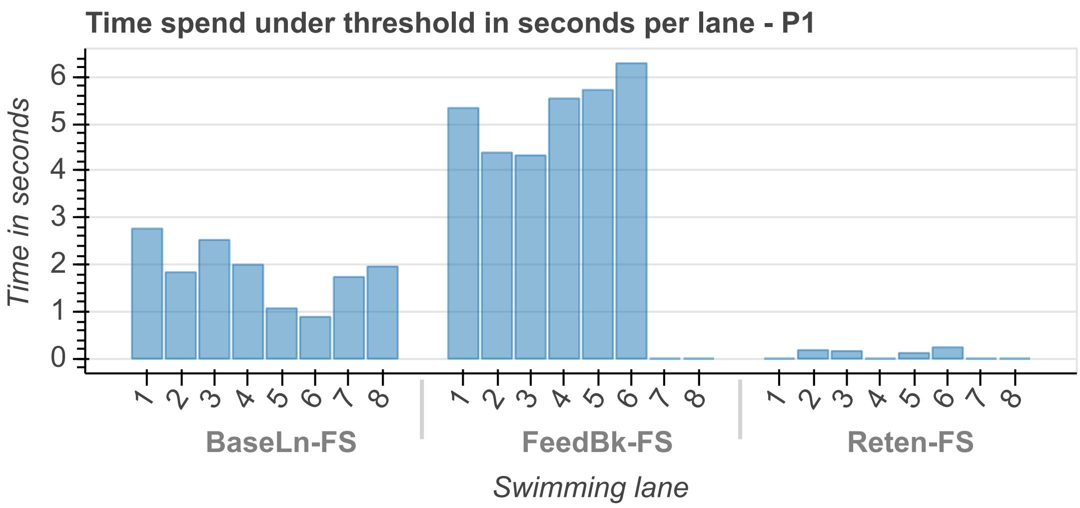

Figure D.2: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.1.2 Back Stroke Body Balance

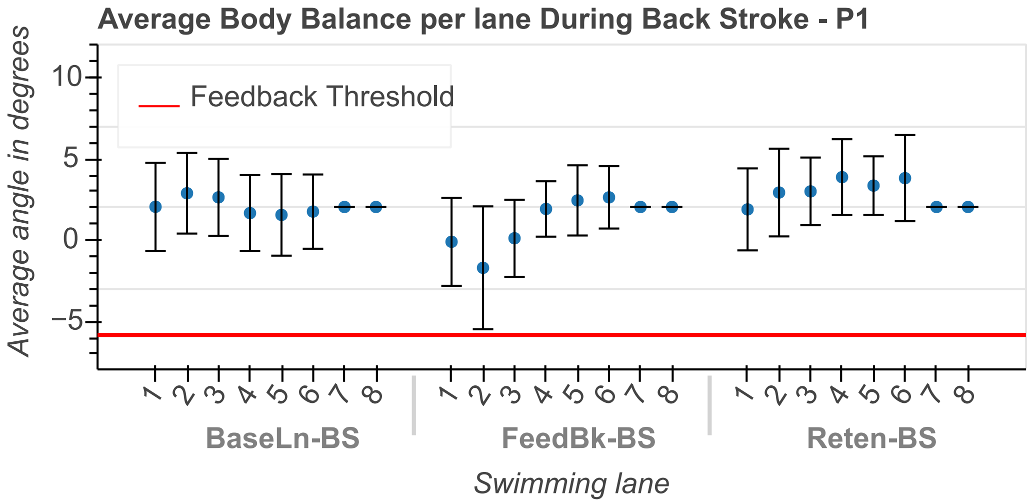

Figure D.3: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

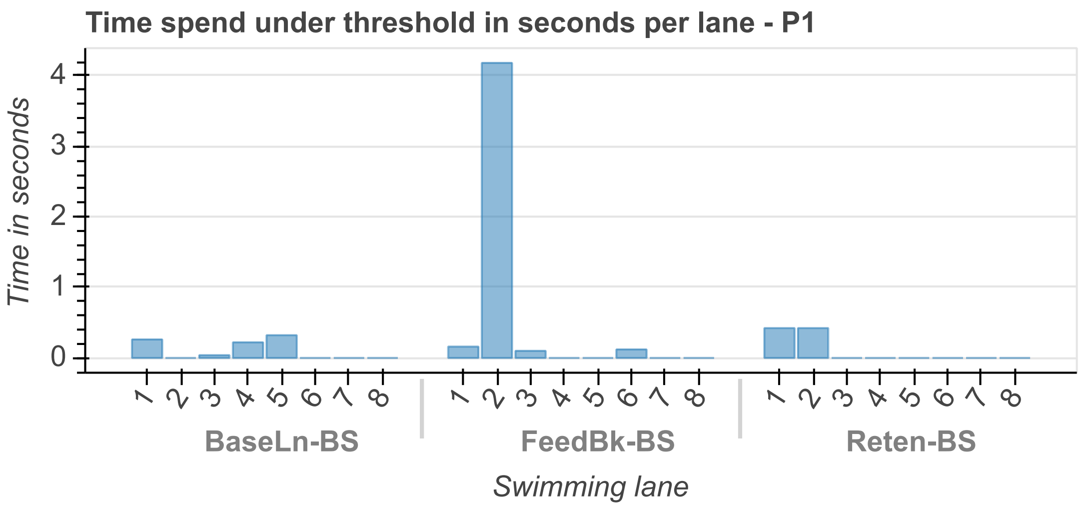

Figure D.4: Cumulative time per lane. feedback responce would be given during the FeedBk session.

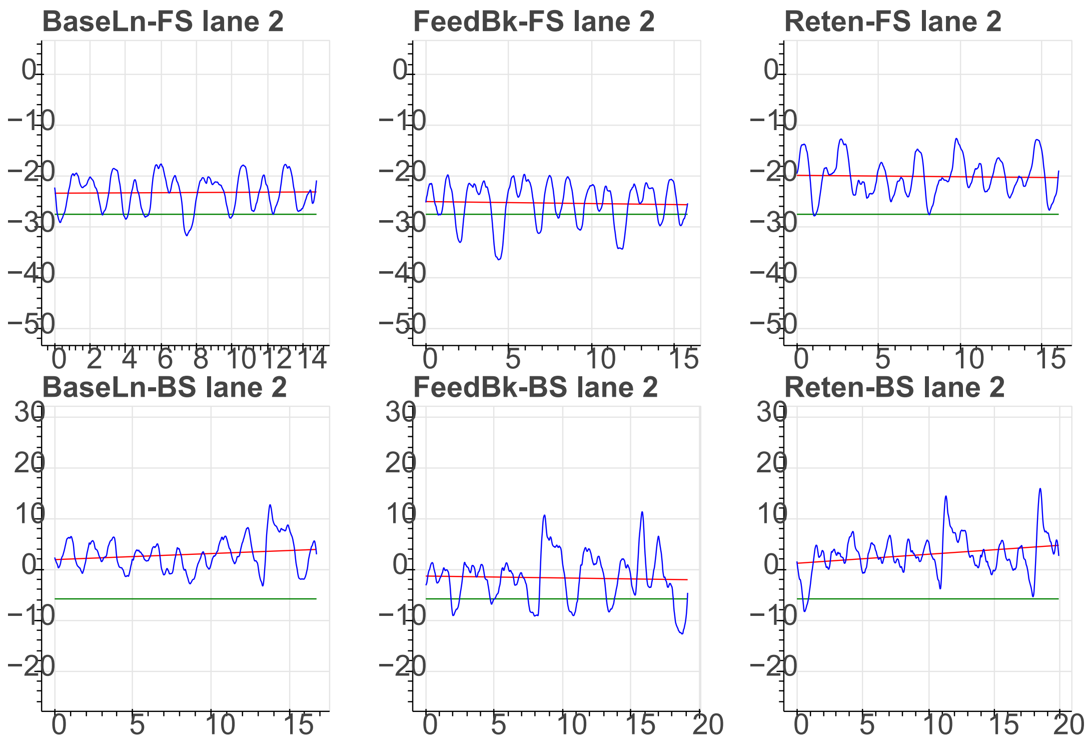

Figure D.5: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*4*	*4*	*4*	*4*	*5*	*4*
Q2	*6*	*5*	*5*	*4*	*5*	*5*
Q3	*5*	*5*	*5*	*2*	*5*	*4*
Q4	*4*	*3*	*4*	*3*	*4*	*4*
MEAN	4.75	4.25	4.5	3.25	4.75	4.25

Table D.1: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.1.3 Qualitative data

Demographics

Age: 24
Sex: female
swimming level: Advanced

Interview

The feedback somtimes felt random. I felt feedback when I wasn't supposed to feel feedback (during bodyroll). I didn't find the actual buzzing annoying. The feedback did not influence the way I was swimming. I think that the wearable could help people become better swimmers, if it was really acurate.
The band was a bit uncomfortable.

D.2 Test P2 Summary

D.2.1 FreeStyle Body Balance

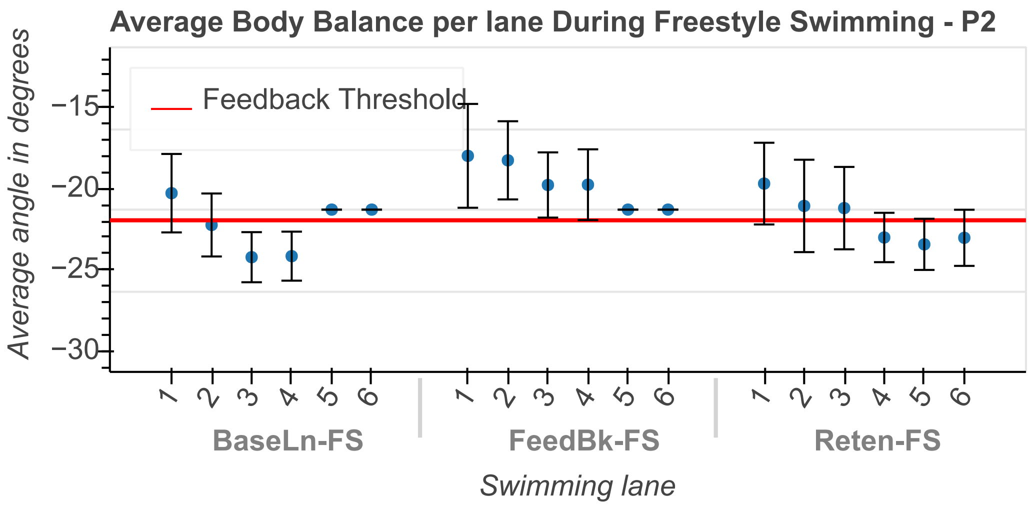

Figure D.6: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

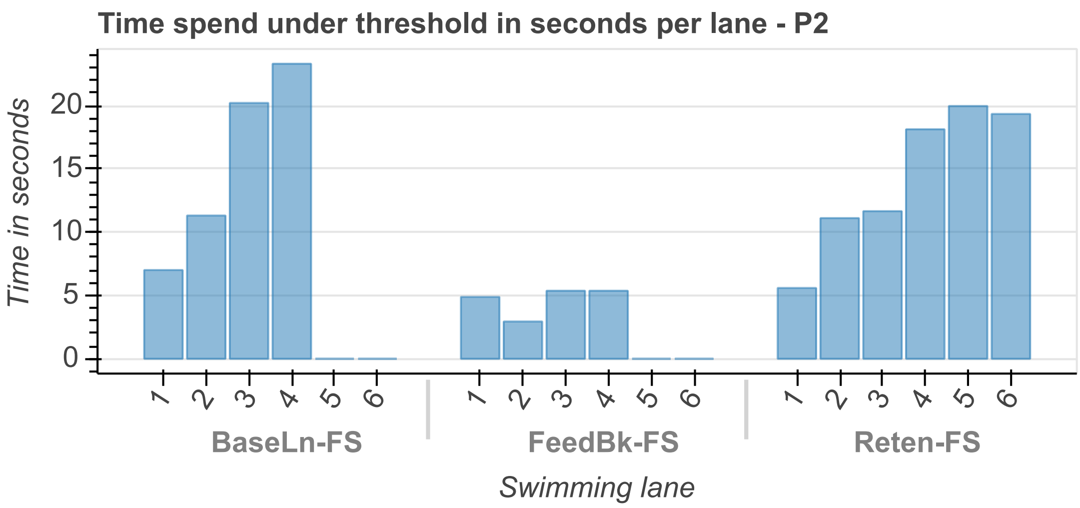

Figure D.7: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.2.2 Back Stroke Body Balance

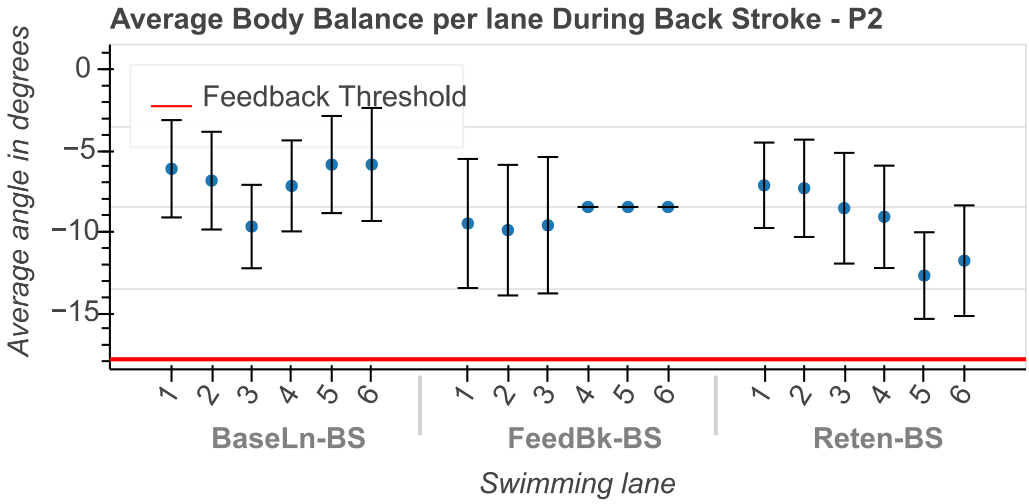

Figure D.8: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

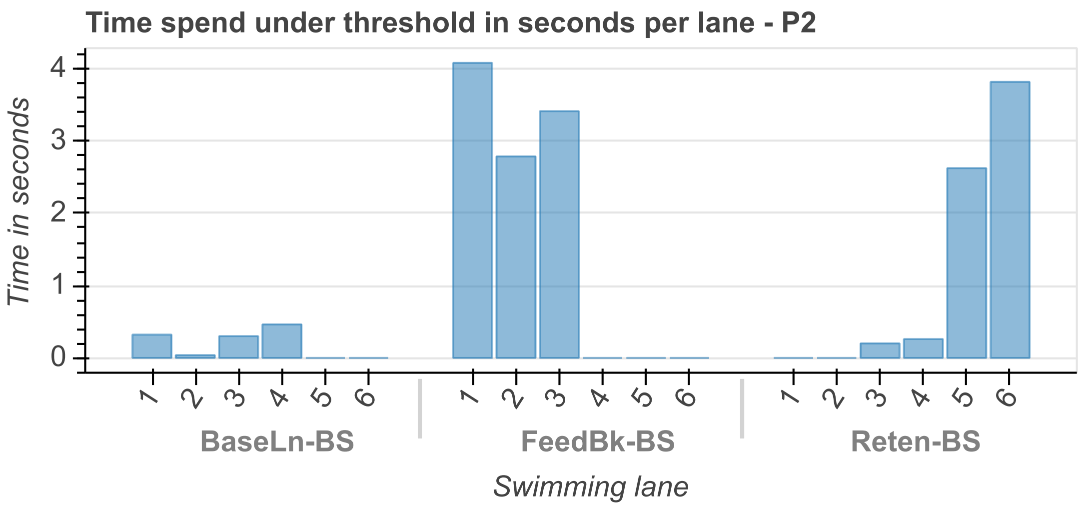

Figure D.9: Cumulative time per lane. feedback responce would be given during the FeedBk session.

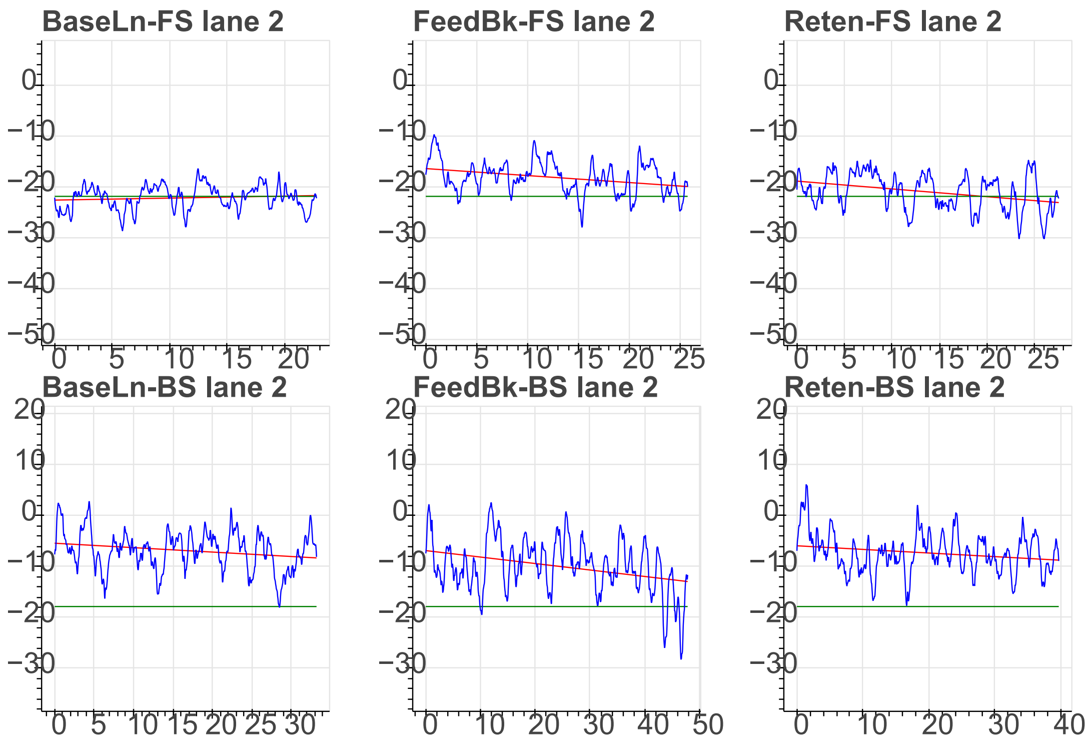

Figure D.10: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*5*	*6*	*6*	*6*	*5*	*2*
Q2	*5*	*6*	*5*	*3*	*6*	*5*
Q3	*4*	*7*	*2*	*2*	*2*	*3*
Q4	*5*	*6*	*5*	*6*	*5*	*4*
MEAN	4.75	6.25	4.5	4.25	4.5	3.5

Table D.2: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.2.3 Qualitative data

Demographics

Age: 21
Sex: male
swimming level: beginner

Interview

I noticed with freestyle when I sank in. I had the feeling that I was laying to far with my head down. I felt the feedback worked better for freestyle than for back stroke. With the back stroke I needed to sink in very far before it did anything. The feedback caused me to lay more straight in the water. I feel like it could help me become a better swiming with freestyle.

D.3 Test P4 Summary

D.3.1 FreeStyle Body Balance

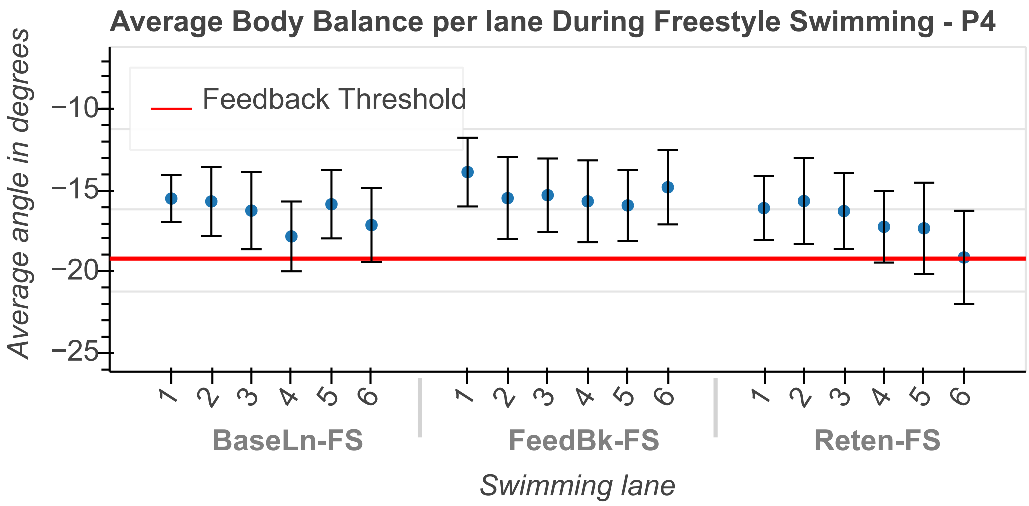

Figure D.11: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

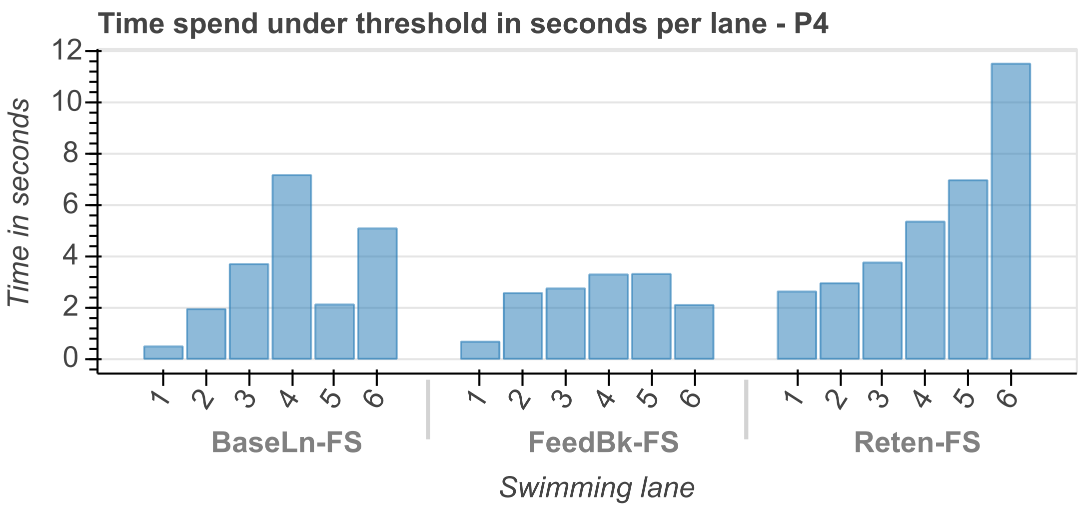

Figure D.12: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.3.2 Back Stroke Body Balance

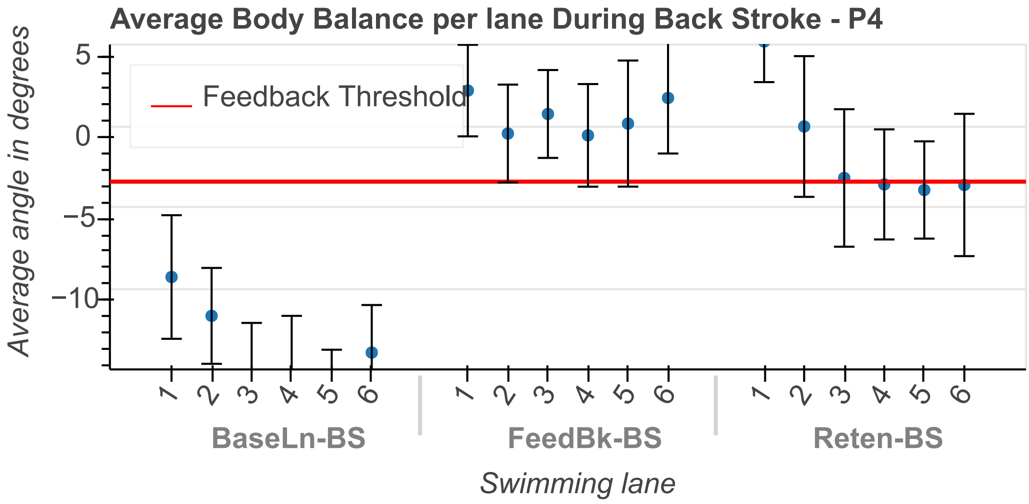

Figure D.13: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

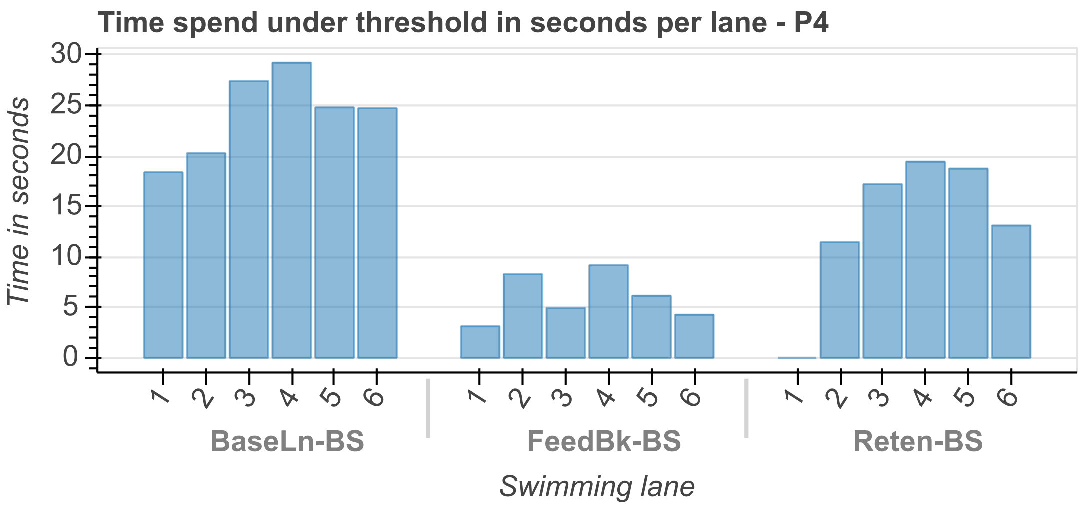

Figure D.14: Cumulative time per lane. feedback responce would be given during the FeedBk session.

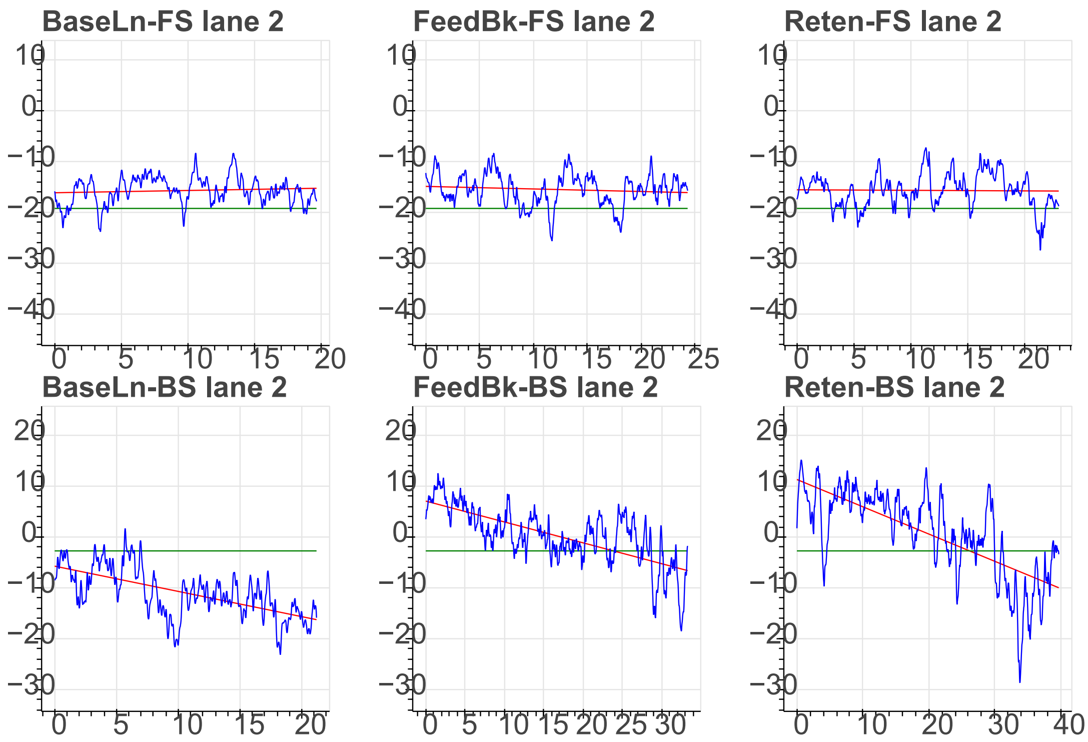

Figure D.15: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*5*	*6*	*4*	*6*	*5*	*5*
Q2	*4*	*7*	*3*	*3*	*6*	*4*
Q3	*3*	*4*	*4*	*6*	*1*	*2*
Q4	*5*	*6*	*3*	*2*	*6*	*3*
MEAN	4.25	5.75	3.5	4.25	4.5	3.5

Table D.3: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.3.3 Qualitative data

Demographics

Age: 21
Sex: male
swimming level: beginner

Interview

In the beginning I found the buzzing very enlightning because you would know to change something, but I noticed mainly with the backstroke that I got used to the vibrations, that caused me to be less aware of the feedback. The feedback was clear and I noticed laying lower in the water when receiving vibrations. I got more tired in the end. that might cause me to forget that the wearable was giving me feedback. Maybe use different feedback patterns to keep you more engaged. I noticed swimming worse when got more tired and I didn't receive the feedback

anymore in the last 12 lanes of back stroke and front crawl. It could help me become a better swimmer.
It would help me if it was less cablely.

D.4 Test P5 Summary

D.4.1 FreeStyle Body Balance

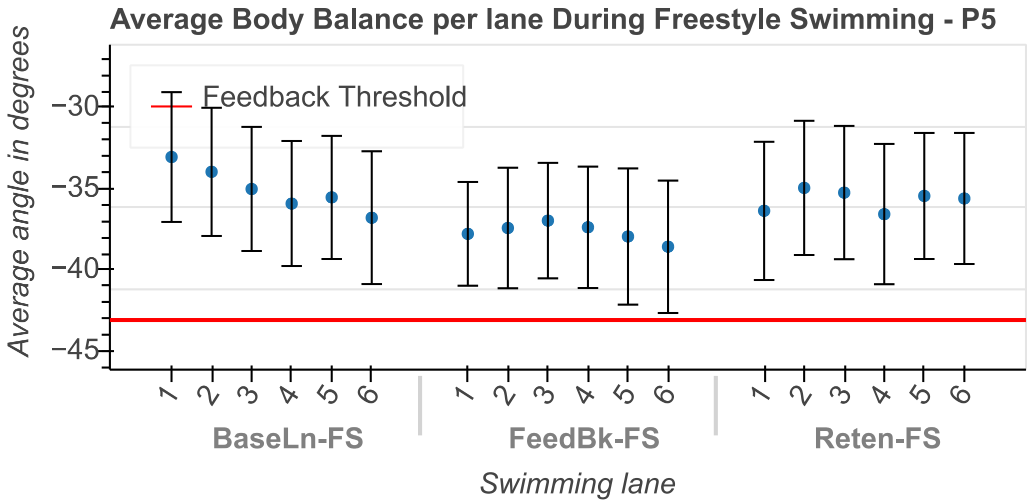

Figure D.16: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

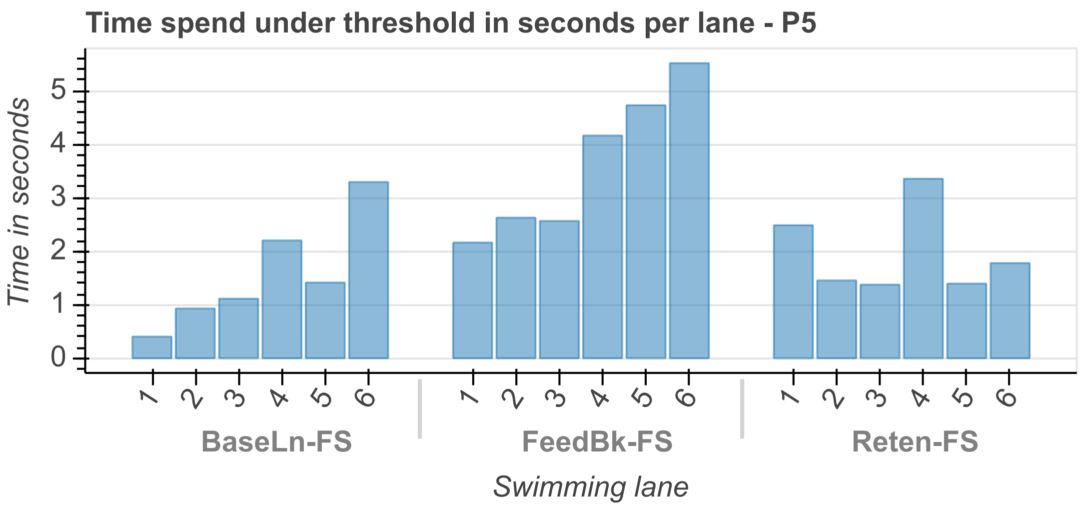

Figure D.17: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.4.2 Back Stroke Body Balance

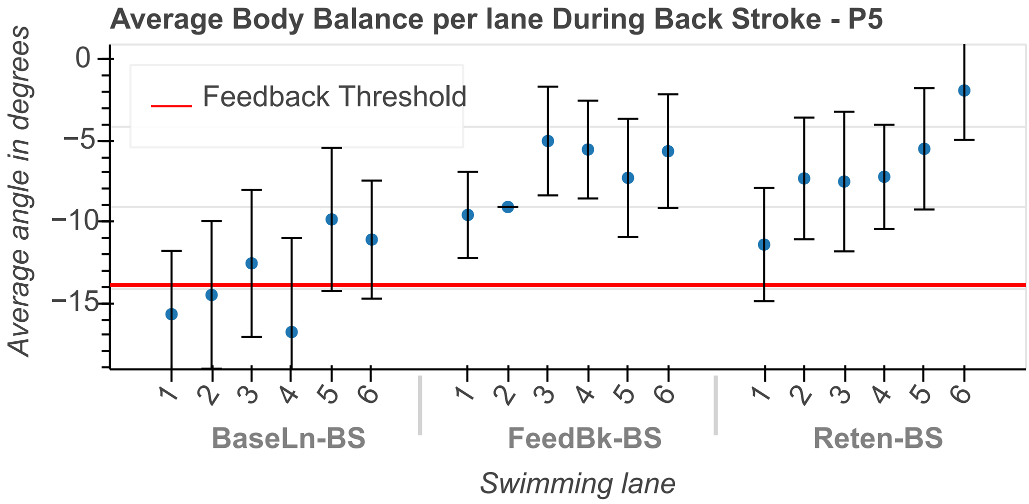

Figure D.18: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

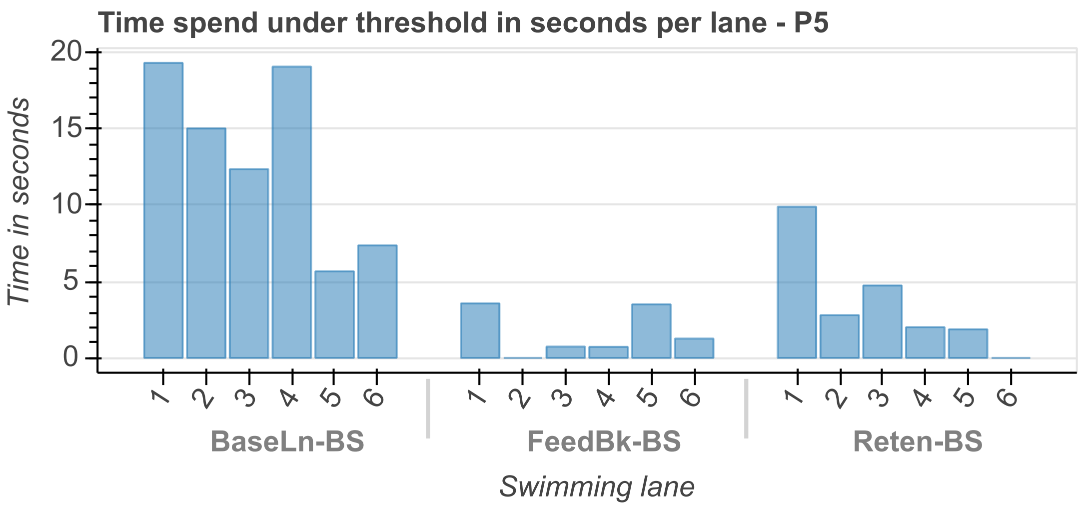

Figure D.19: Cumulative time per lane. feedback responce would be given during the FeedBk session.

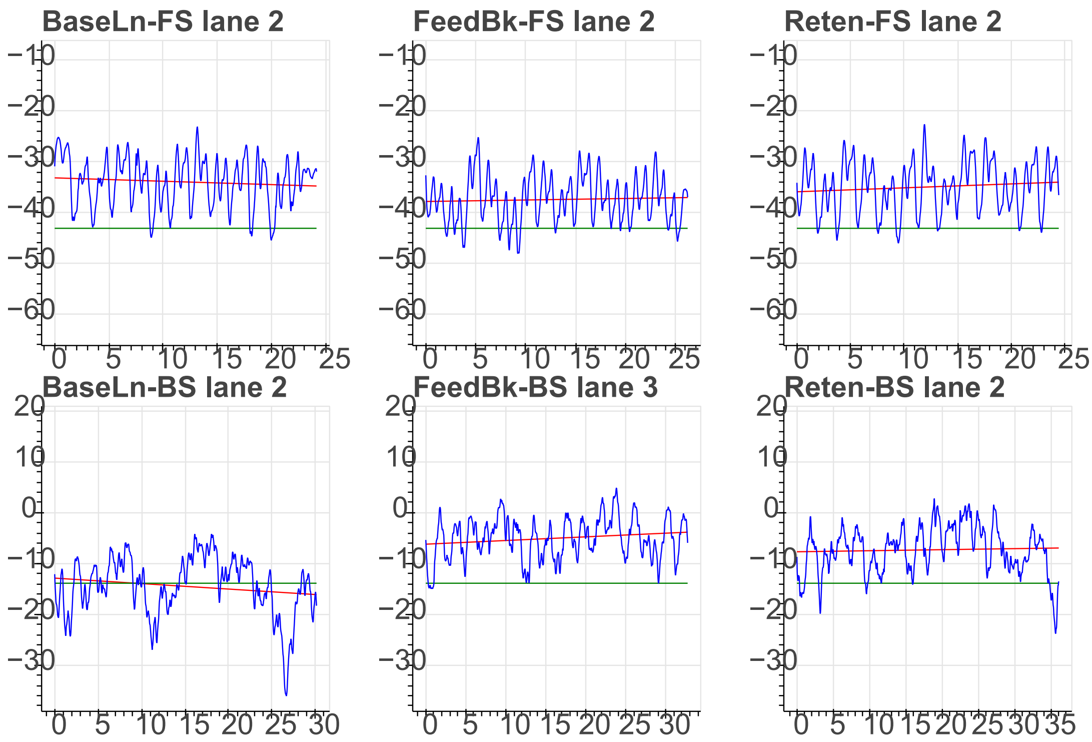

Figure D.20: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*5*	*5*	*6*	*5*	*5*	*6*
Q2	*5*	*6*	*6*	*3*	*6*	*5*
Q3	*5*	*3*	*5*	*5*	*4*	*3*
Q4	*4*	*5*	*6*	*3*	*5*	*4*
MEAN	4.75	4.75	5.75	4.0	5.0	4.5

Table D.4: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.4.3 Qualitative data

Demographics

Age: 25
Sex: male
swimming level: beginner

Interview

I liked the feedback during the glide phase, but I felt like it gave feedback during the bodyroll as well, mainly during the freestyle swimming. It was clear what the feedback meant. It might help me become a better swimmer, but mostly at the start.

D.5 Test P6 Summary

D.5.1 FreeStyle Body Balance

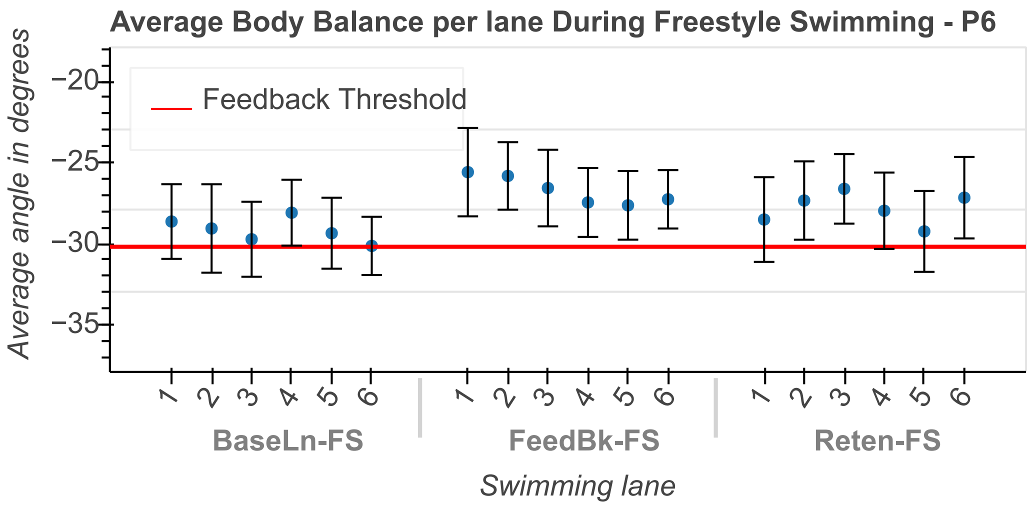

Figure D.21: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

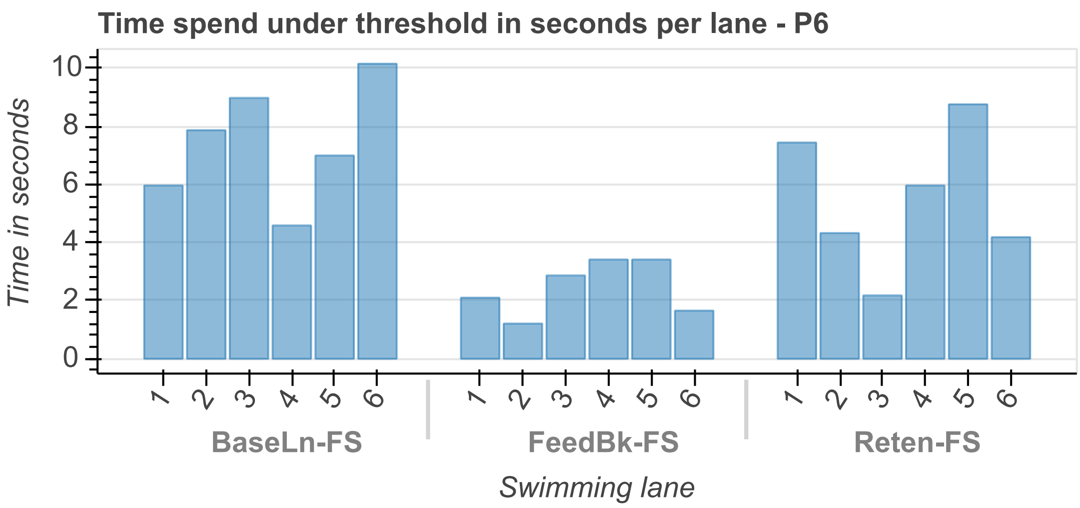

Figure D.22: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.5.2 Back Stroke Body Balance

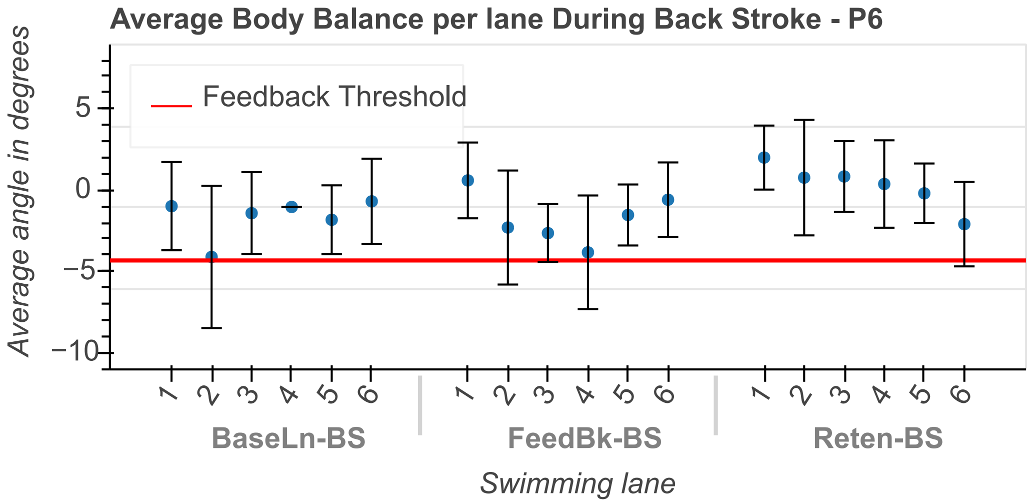

Figure D.23: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

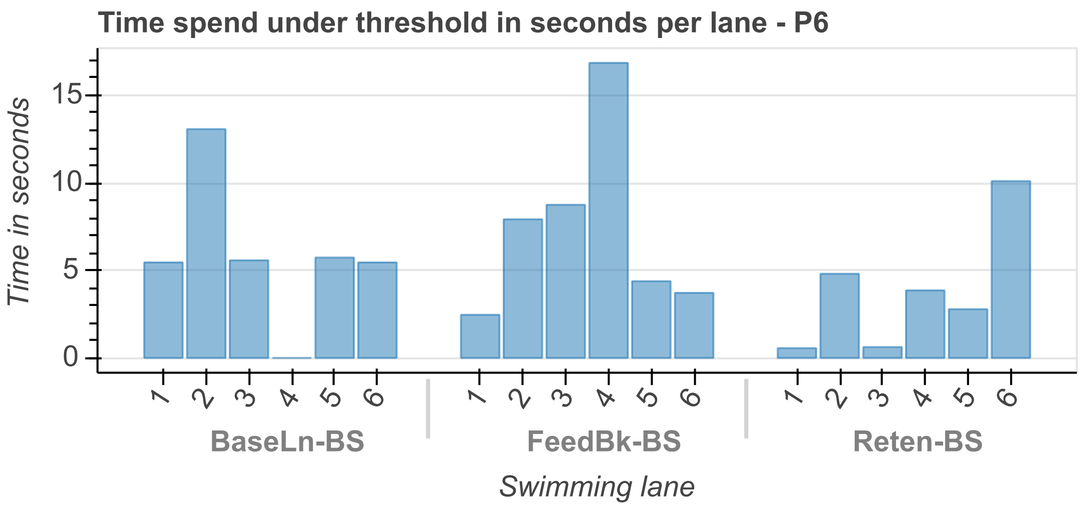

Figure D.24: Cumulative time per lane. feedback responce would be given during the FeedBk session.

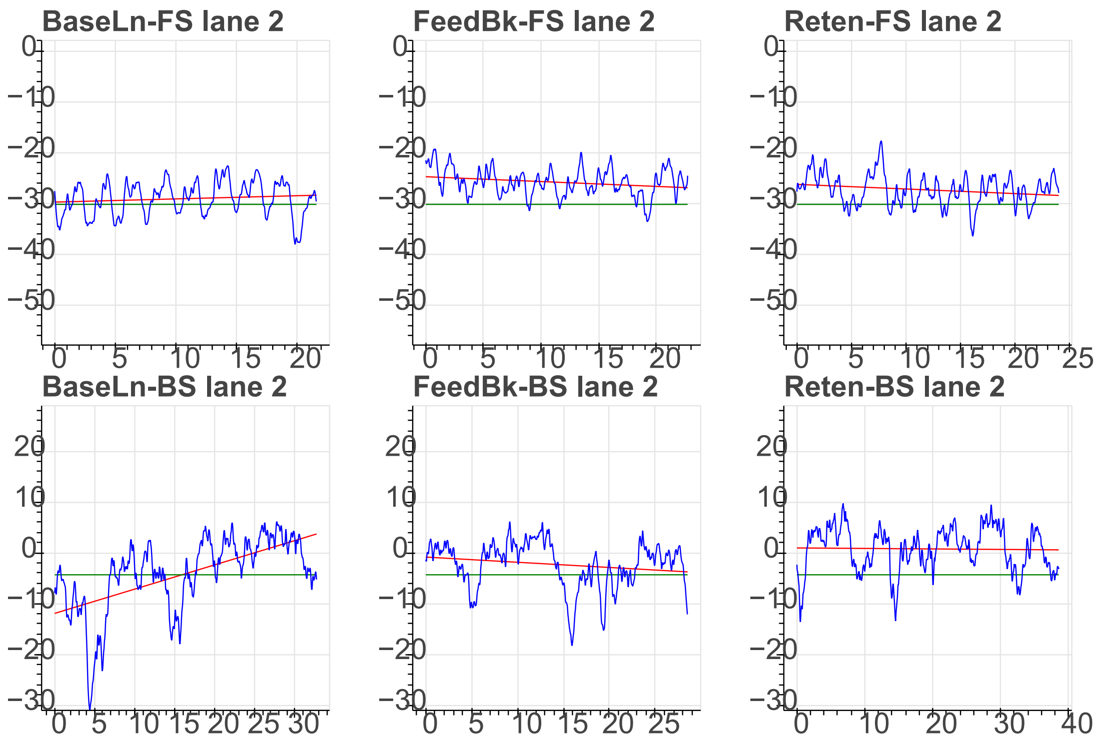

Figure D.25: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*2*	*6*	*5*	*6*	*4*	*6*
Q2	*4*	*5*	*6*	*5*	*6*	*6*
Q3	*3*	*4*	*5*	*6*	*5*	*6*
Q4	*5*	*6*	*7*	*6*	*6*	*6*
MEAN	3.5	5.25	5.75	5.75	5.25	6.0

Table D.5: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.5.3 Qualitative data

Demographics

Age: 30
Sex: male
swimming level: average

Interview

I thought it was very useful to correct your posture. With backstroke, when you correct your posture it also buzzed and at some point it's enough, but generally useful. The feedback was clear. The feedback had influence on the way I was swimming. It could help me become a better swimmer.
The calibration seems difficult... I feel like it has influence on the results

D.6 Test P7 Summary

D.6.1 FreeStyle Body Balance

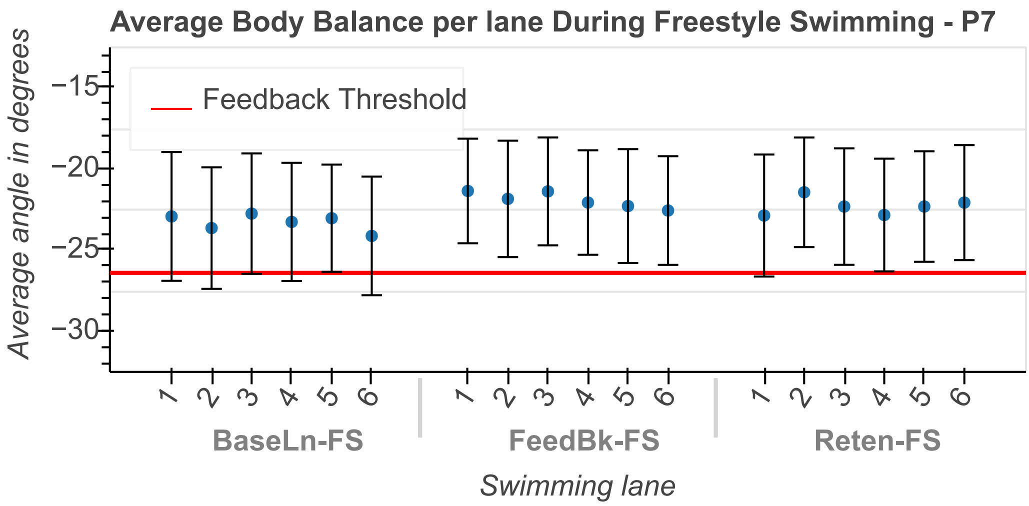

Figure D.26: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

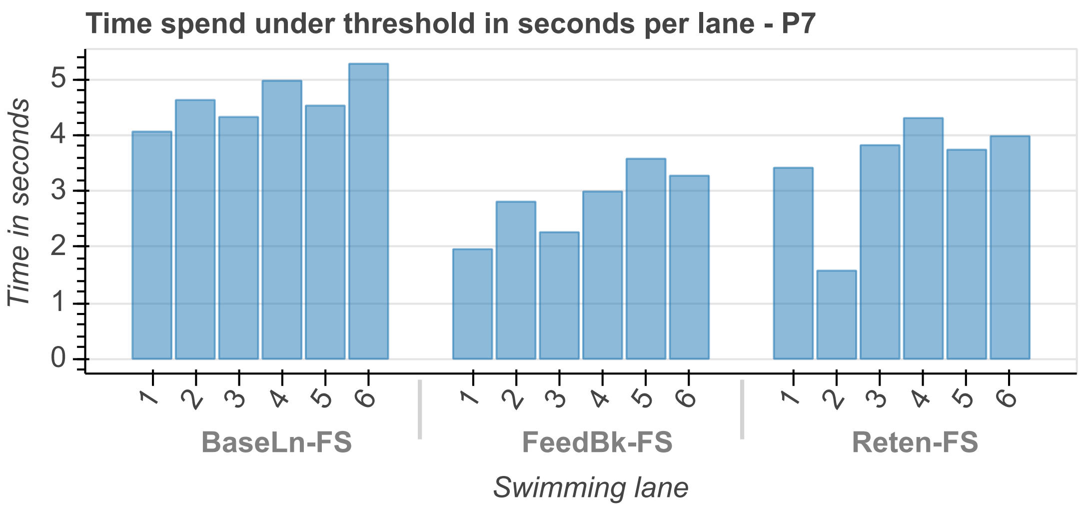

Figure D.27: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.6.2 Back Stroke Body Balance

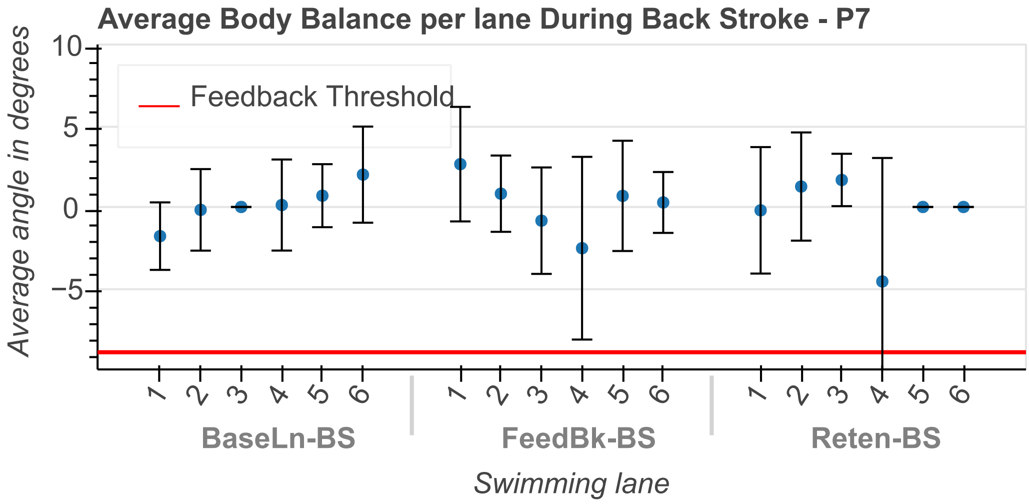

Figure D.28: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

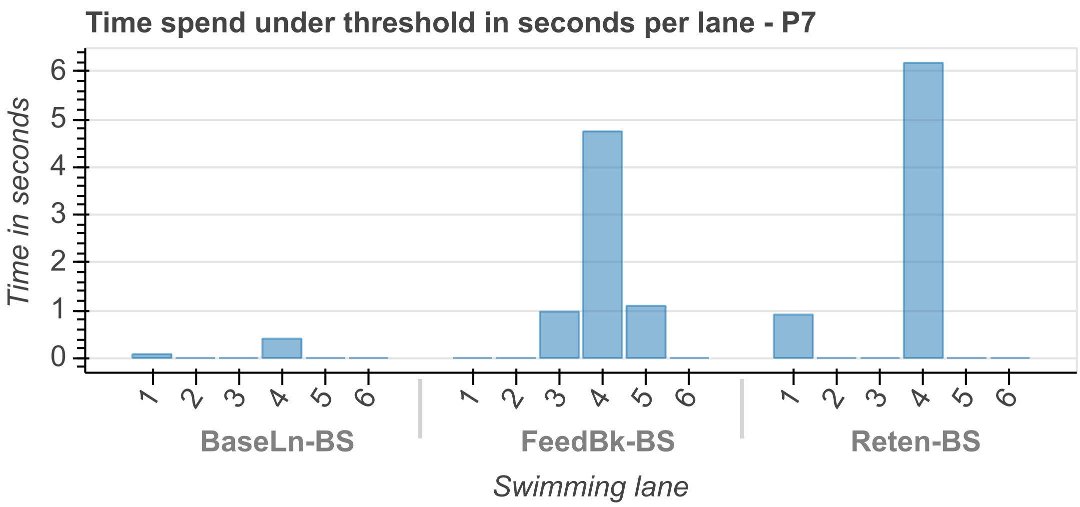

Figure D.29: Cumulative time per lane. feedback responce would be given during the FeedBk session.

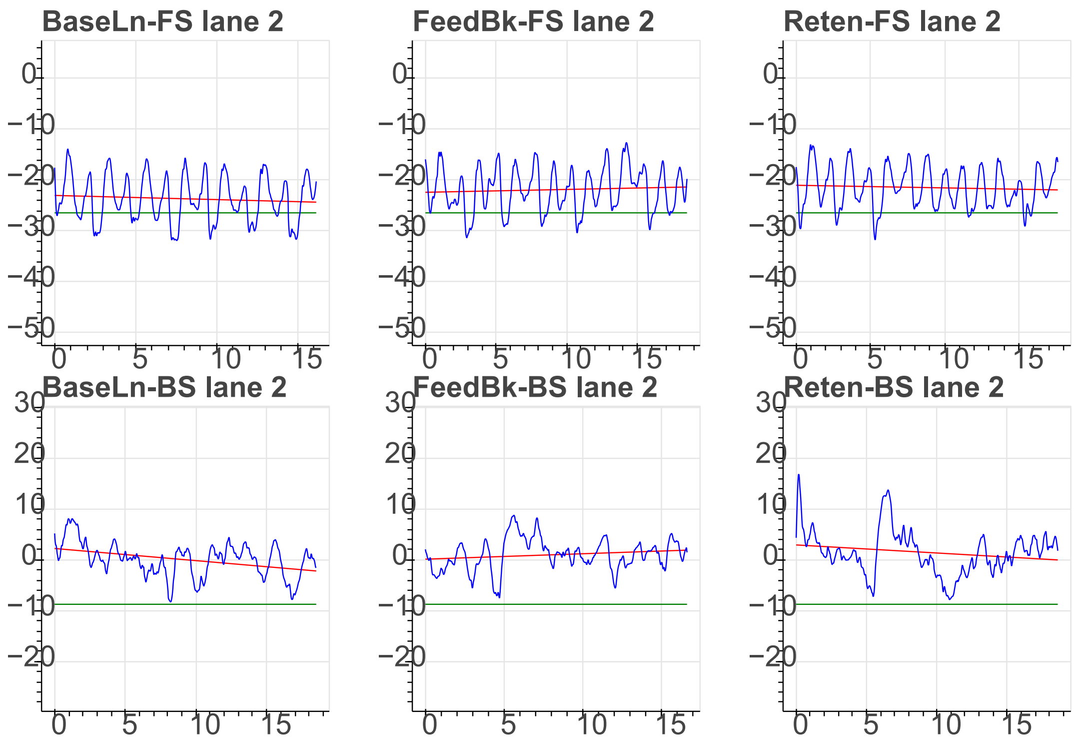

Figure D.30: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*6*	*7*	*5*	*7*	*7*	*3*
Q2	*2*	*5*	*3*	*6*	*5*	*5*
Q3	*3*	*7*	*4*	*5*	*5*	*3*
Q4	*6*	*6*	*5*	*6*	*7*	*6*
MEAN	4.25	6.25	4.25	6.0	6.0	4.25

Table D.6: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.6.3 Qualitative data

Demographics

Age: 21
Sex: male
swimming level: Advanced

Interview

I liked the vibration in the direction of the breathing, but it would trigger on normal bodyroll. for the backstroke I liked that it gave feedback when my butt was to low. And too bad that it vibrated during turning as well. It gave a bit too much feedback genrally. I was more attentive on my bodybalance during swimming. It could help me become a better swimmer if it gave the feedback during the right sections of swimming. I think the vibrations are a bit too intence. When pushing of the wall, the straps would flip outward. It had a bit of friction at the ribs

D.7 Test P8 Summary

D.7.1 FreeStyle Body Balance

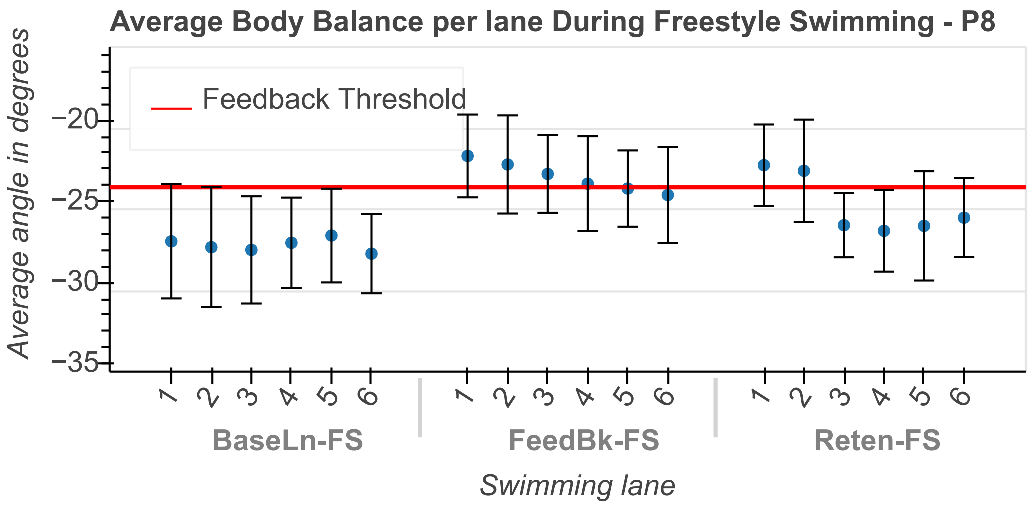

Figure D.31: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

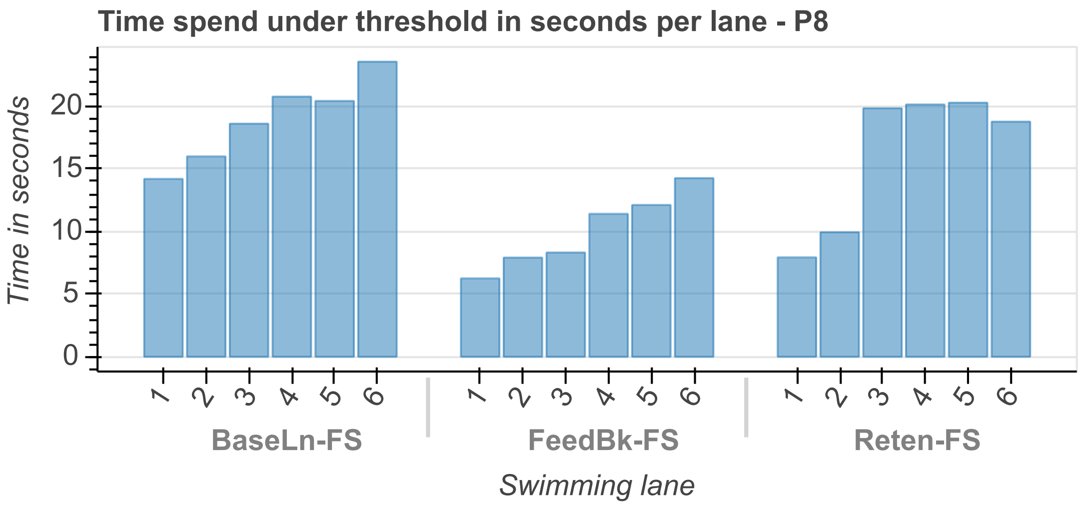

Figure D.32: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.7.2 Back Stroke Body Balance

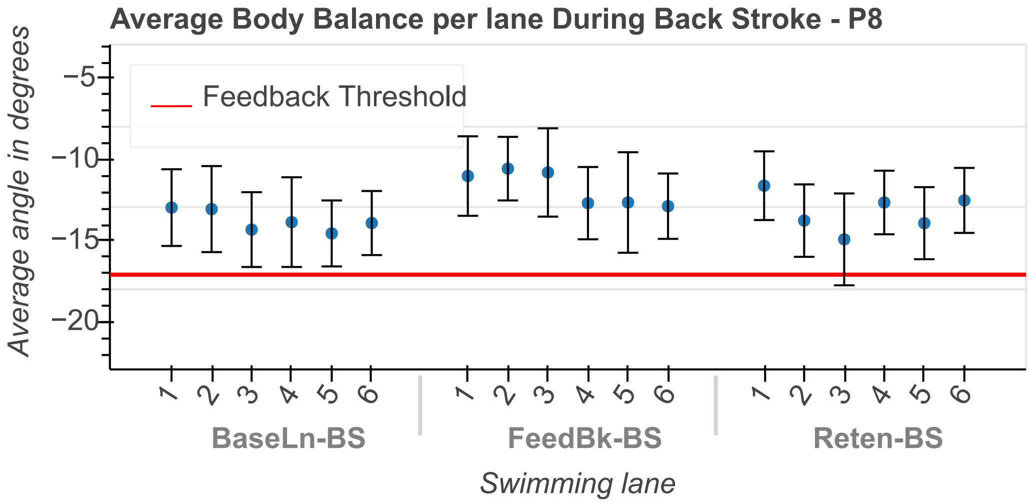

Figure D.33: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

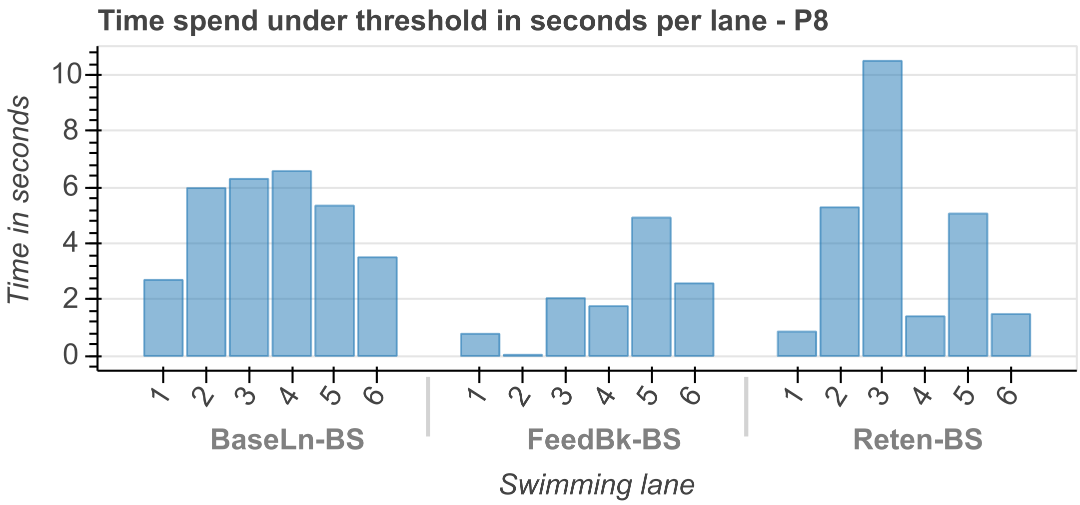

Figure D.34: Cumulative time per lane. feedback responce would be given during the FeedBk session.

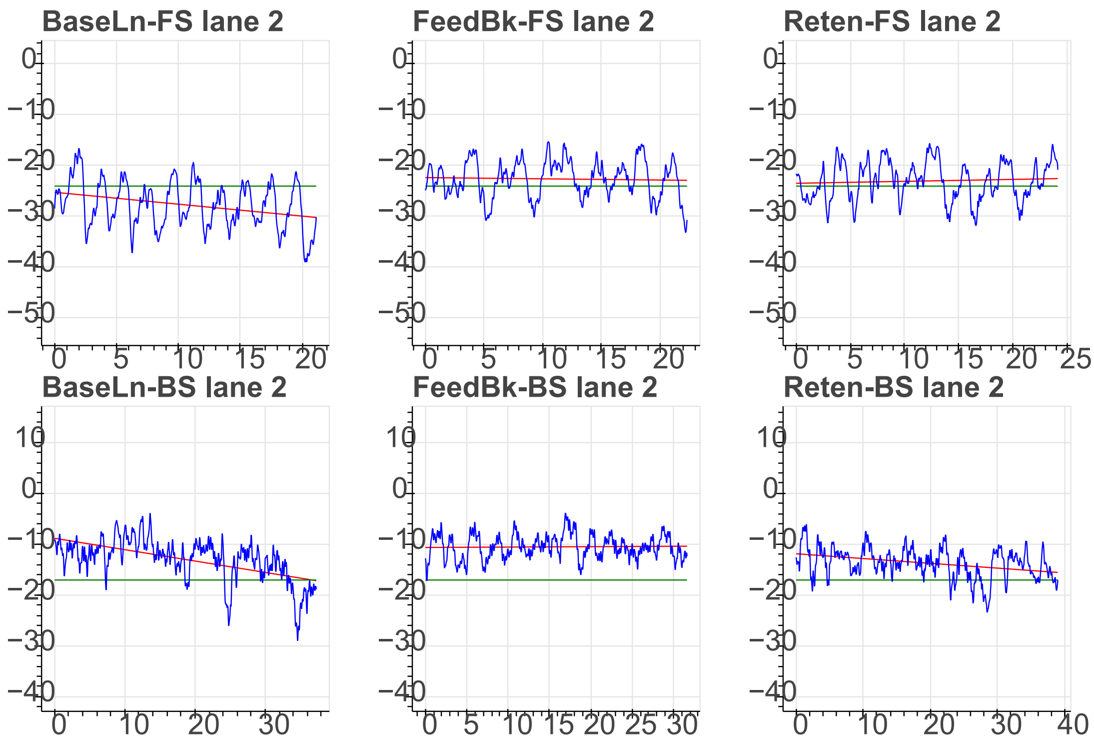

Figure D.35: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*2*	*5*	*2*	*6*	*6*	*6*
Q2	*2*	*4*	*2*	*5*	*4*	*4*
Q3	*3*	*5*	*4*	*6*	*2*	*2*
Q4	*3*	*3*	*3*	*4*	*4*	*3*
MEAN	2.5	4.25	2.75	5.25	4.0	3.75

Table D.7: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.7.3 Qualitative data

Demographics

Age: 31
Sex: male
swimming level: average

Interview

I like the system. I can very easily feel it. During freestyle it mostly went off when breathing and sometimes when turing too much on one side. I think that helped. It was clear what the feedback meant. For backstroke I mainly got vibrations when getting tangled in the wires. I did try to adjust to the feedback. I think that this wearable could help me become a better swimmer, especially for my breating.
The whole apparatus was more comfortable to wear in the water. Outside the water it was a bit

tight.

D.8 Test P9 Summary

D.8.1 FreeStyle Body Balance

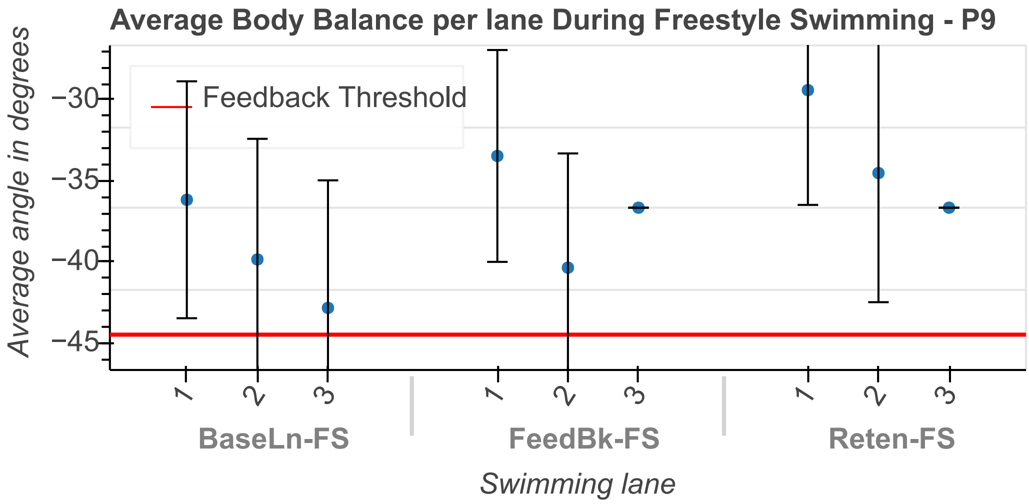

Figure D.36: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

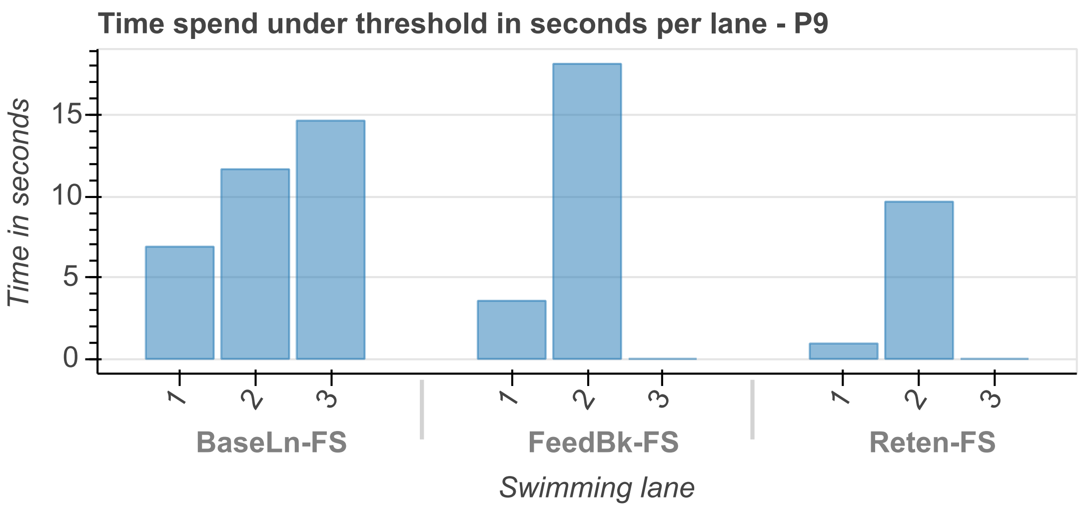

Figure D.37: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.8.2 Back Stroke Body Balance

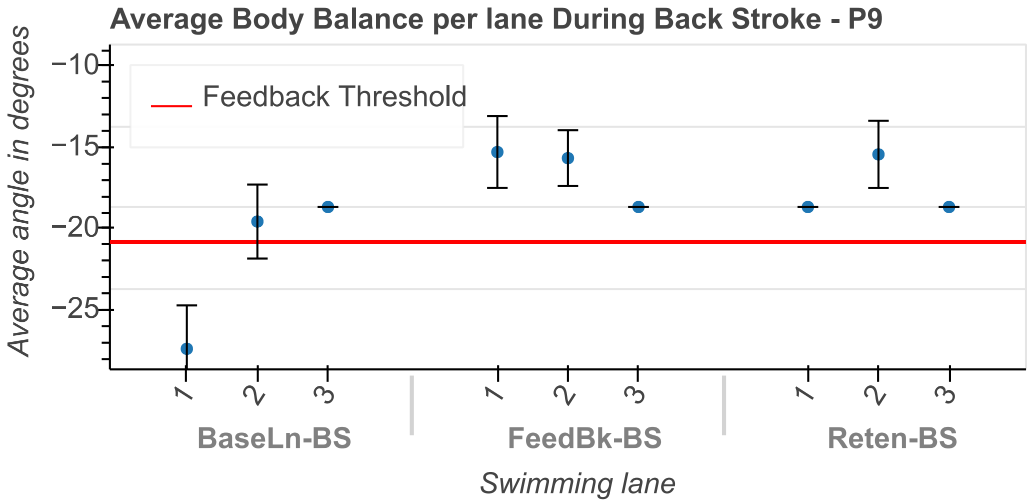

Figure D.38: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

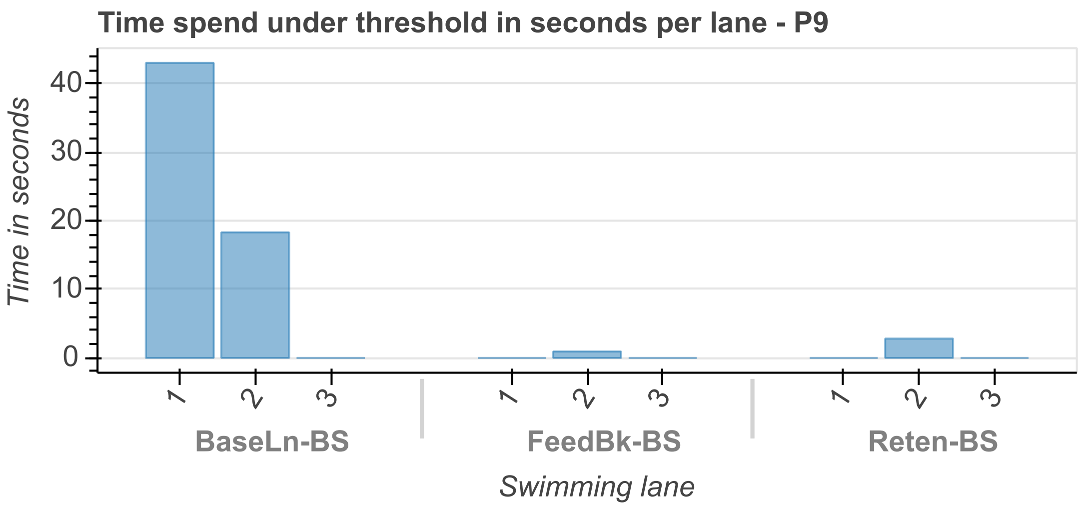

Figure D.39: Cumulative time per lane. feedback responce would be given during the FeedBk session.

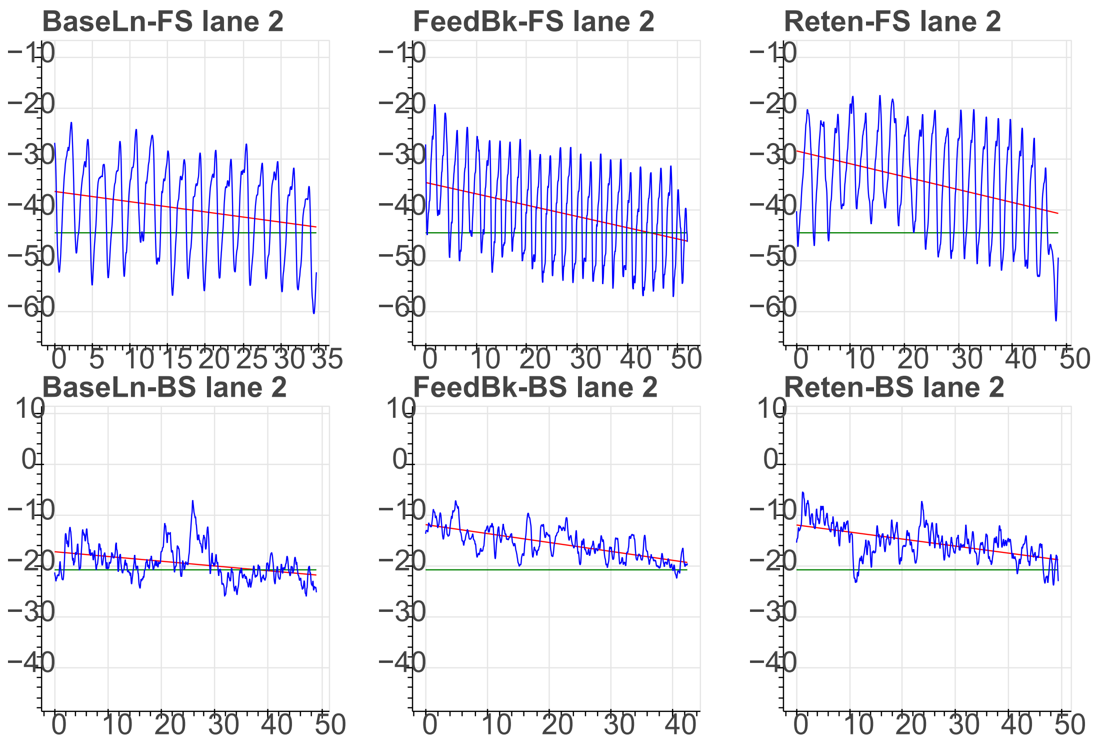

Figure D.40: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	**FeedBk_FS**	**Reten_FS**	**BaseLn_BS**	**FeedBk_BS**	**Reten_BS**
Q1	*3*	*3*	*6*	*5*	*6*	*6*
Q2	*5*	*6*	*6*	*5*	*6*	*6*
Q3	*3*	*3*	*5*	*3*	*5*	*6*
Q4	*3*	*5*	*6*	*5*	*6*	*6*
MEAN	3.5	4.25	5.75	4.5	5.75	6.0

Table D.8: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.8.3 Qualitative data

Demographics

Age: 60
Sex: male
swimming level: beginner

Interview

I liked the way the sensor worked, and that the feedback reacted to your posture in the water. I think I got vibrations when I needed to receive them when the sensitivity (calibration) was good. The vibrations improved my posture in the water. You try to focus on the feedback and that is the important thing, I think. I think it could help me become a better swimmer.

D.9 Test P10 Summary

D.9.1 FreeStyle Body Balance

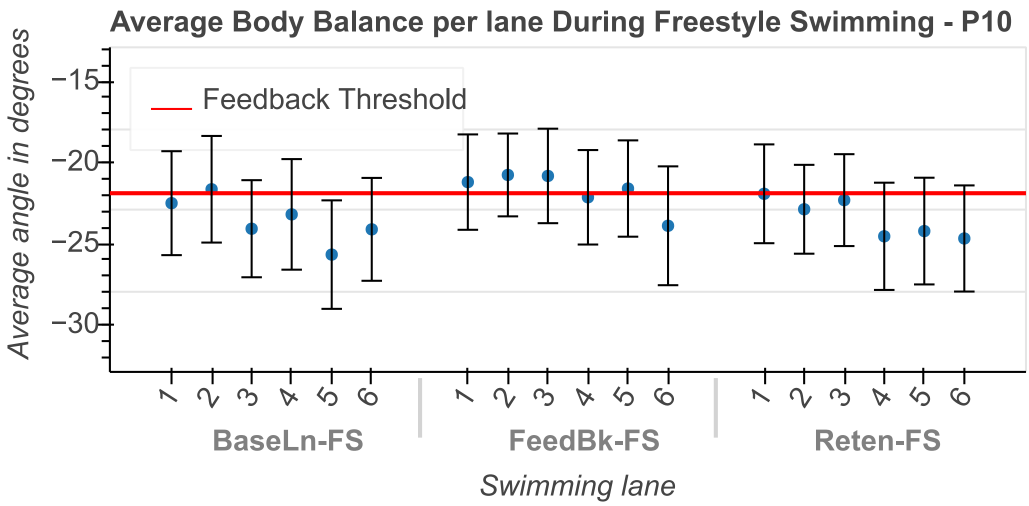

Figure D.41: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

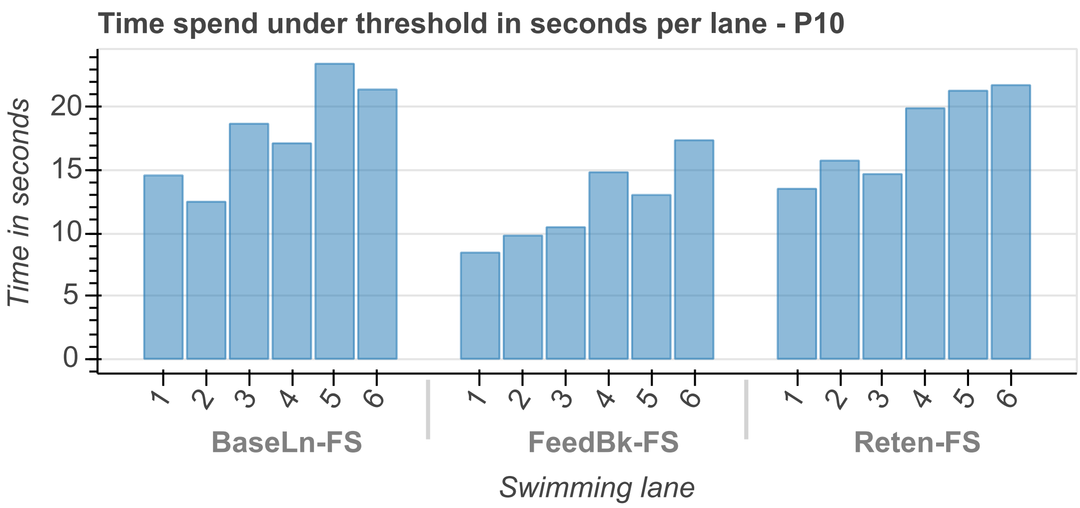

Figure D.42: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.9.2 Back Stroke Body Balance

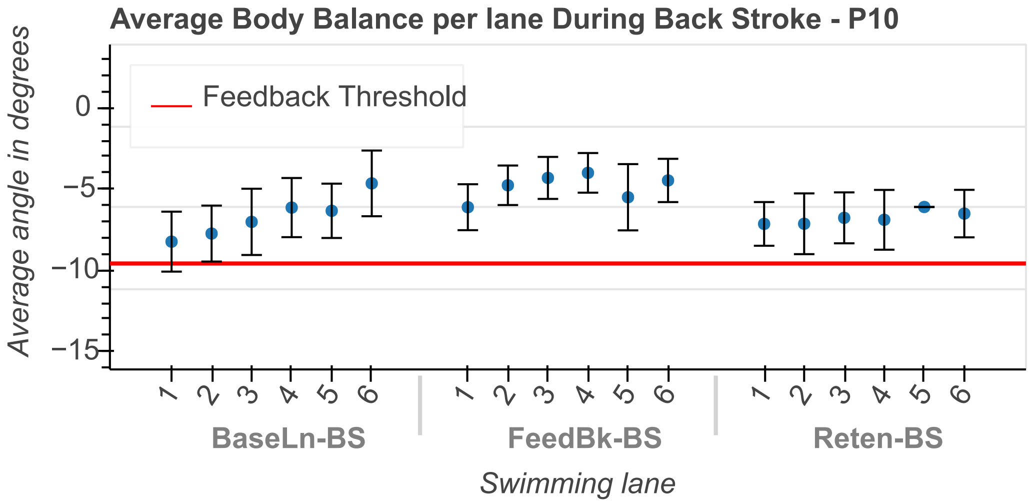

Figure D.43: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

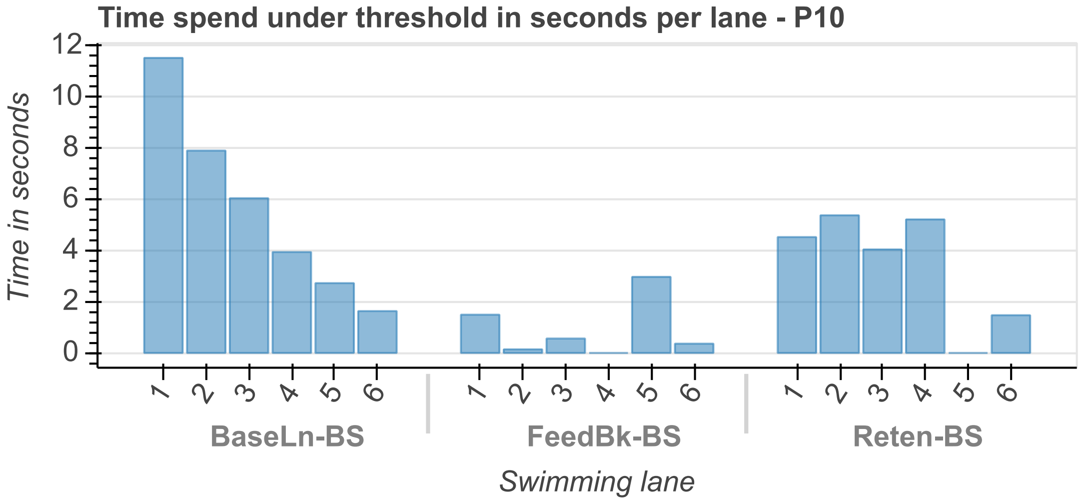

Figure D.44: Cumulative time per lane. feedback responce would be given during the FeedBk session.

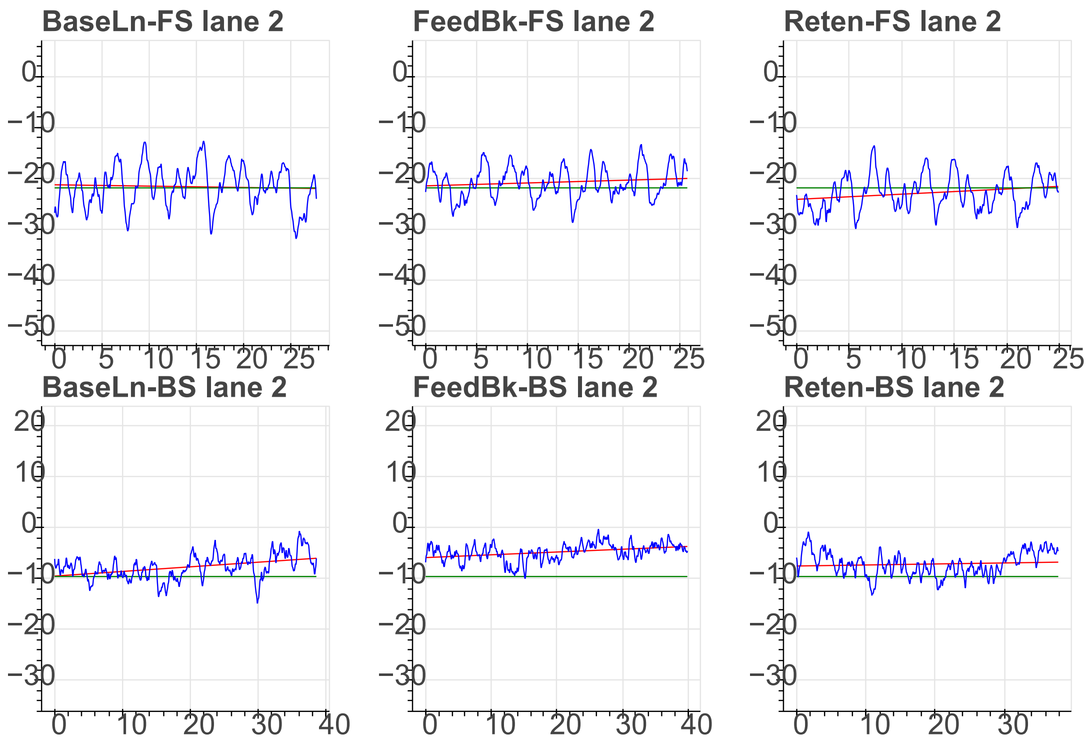

Figure D.45: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*2*	*6*	*5*	*5*	*2*	*6*
Q2	*5*	*6*	*4*	*6*	*7*	*6*
Q3	*6*	*4*	*5*	*2*	*7*	*6*
Q4	*4*	*6*	*5*	*5*	*7*	*6*
MEAN	4.25	5.5	4.75	4.5	5.75	6.0

Table D.9: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.9.3 Qualitative data

Demographics

Age: 34
Sex: male
swimming level: intermediate

Interview

The vibrations match my intuition. In backstroke I most definatly received vibrations when I needed to receive vibrations. In freestyle less so, it also gave be feedack when I turned to breath. The feedback caused me to pay more attention to my posture in the water. I was swimming cleaner with vibrations. It could maybe help me with my posture in the water. It might be more useful when I'm tired, I wasn't really super tired.
The band caused me to not be able to breath as freely as I could be. I noticed the wearable on

the point of my back. I felt the wearable on my ribcage which made it less nice to swim.

D.10 Test P11 Summary

D.10.1 FreeStyle Body Balance

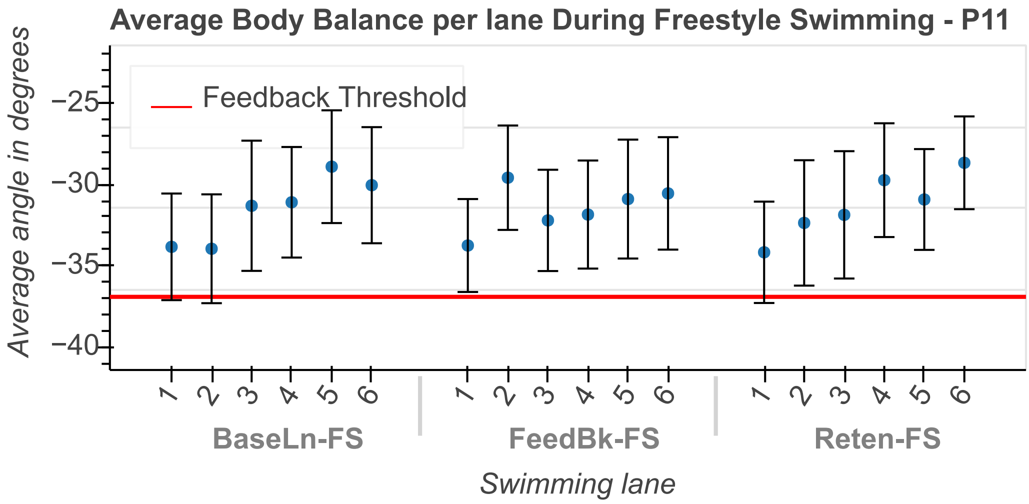

Figure D.46: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

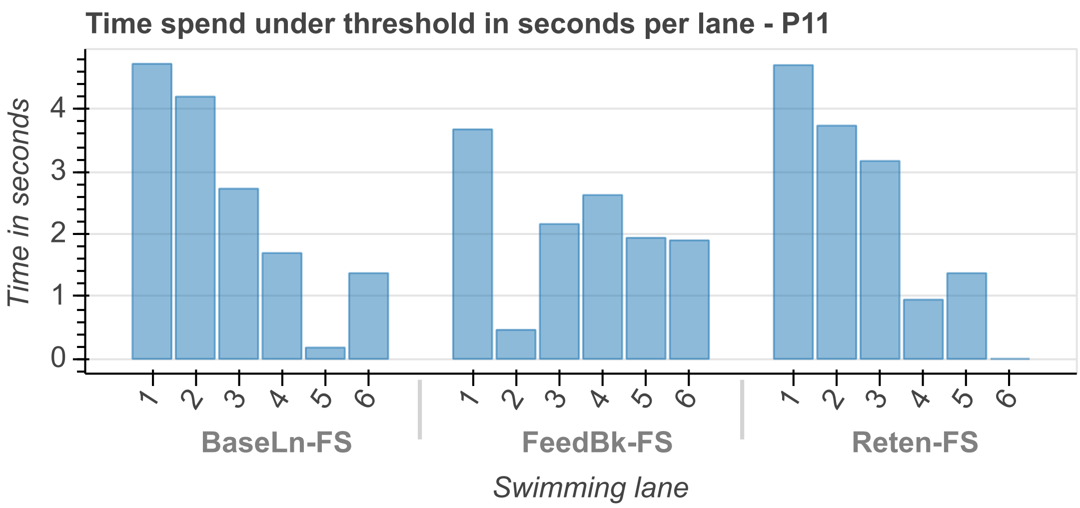

Figure D.47: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.10.2 Back Stroke Body Balance

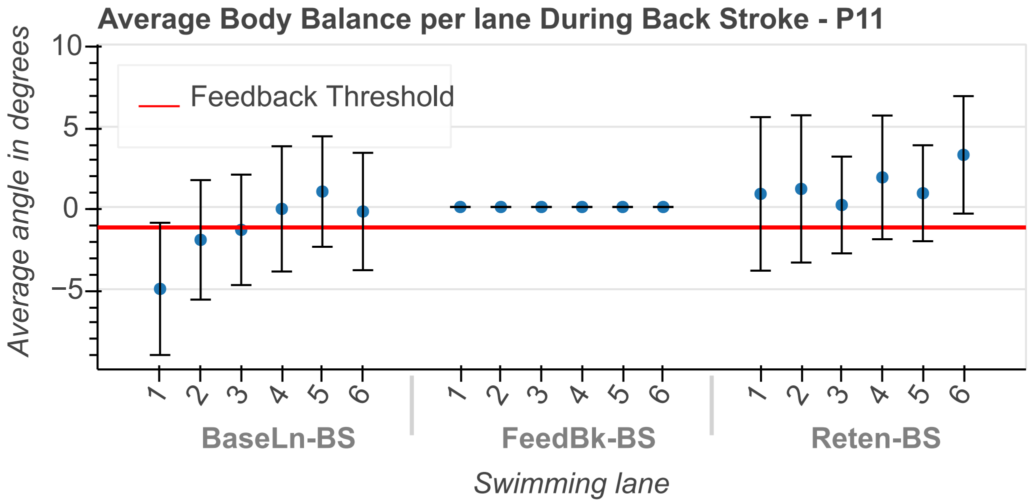

Figure D.48: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

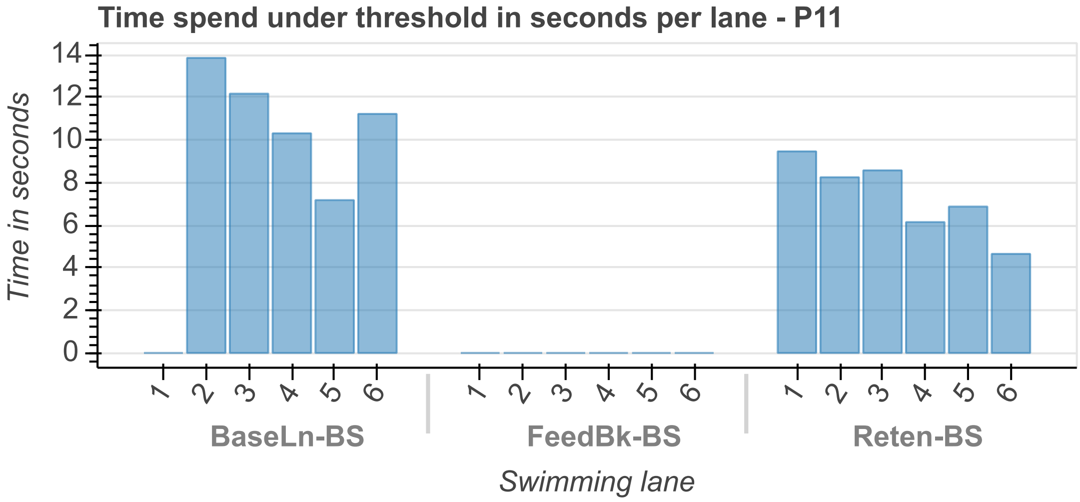

Figure D.49: Cumulative time per lane. feedback responce would be given during the FeedBk session.

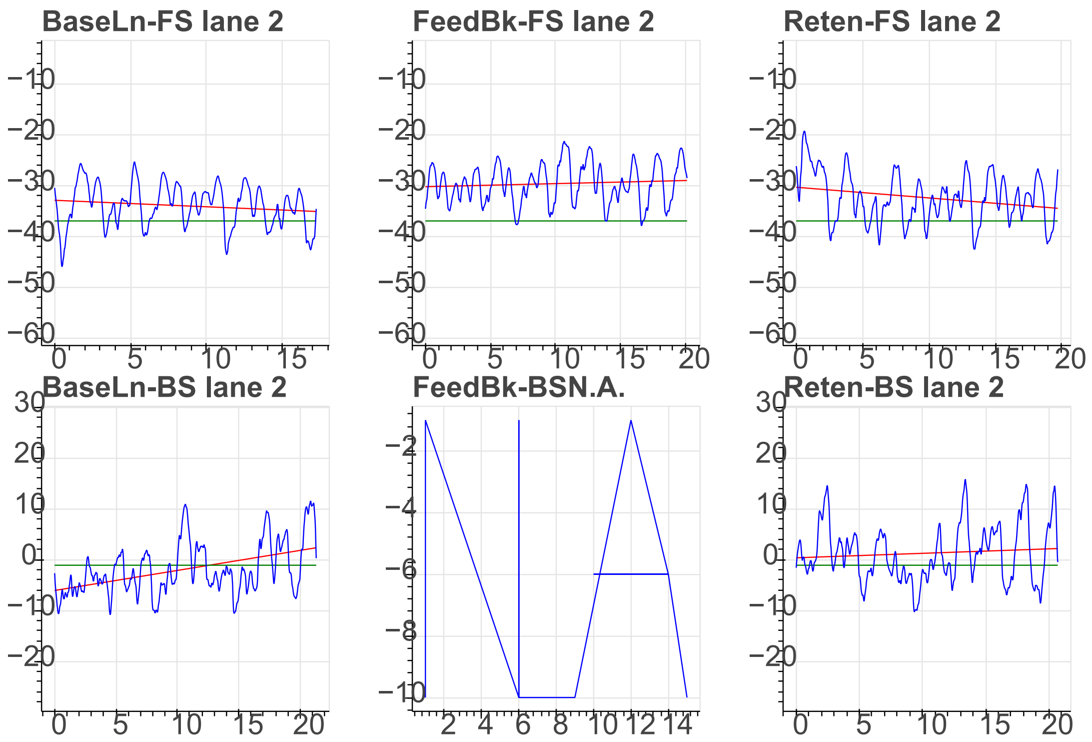

Figure D.50: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*5*	*6*	*4*	*3*	*5*	*5*
Q2	*6*	*5*	*6*	*3*	*6*	*4*
Q3	*3*	*4*	*3*	*3*	*3*	*4*
Q4	*4*	*5*	*6*	*3*	*6*	*6*
MEAN	4.5	5.0	4.75	3.0	5.0	4.75

Table D.10: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.10.3 Qualitative data

Demographics

Age: 23
Sex: female
swimming level: intermediate

Interview

The feedback made me more aware of my balance and posture. For the freestyle it was a bit random. But when I swam after the feedack I was made more aware of my body posture. For freesyle the feedback was not very clear. Most of the times when I took a breath it vibrated. And of course when I got tired I received more feedback which is logical, but it felt a bit random sometimes. For the backstroke it was more clear, but I didn't receive much feedback. For the backstroke the feedback had influence on how I was swimming, I got more tired during the run and noticed that I got feedback at the end when my feet started to lower. So I adjusted my angle acordingly. I do think the wearable got help me with a bit more work on it. because you do get live feedback wich I miss a lot here in swimming.

D.11 Test P12 Summary

D.11.1 FreeStyle Body Balance

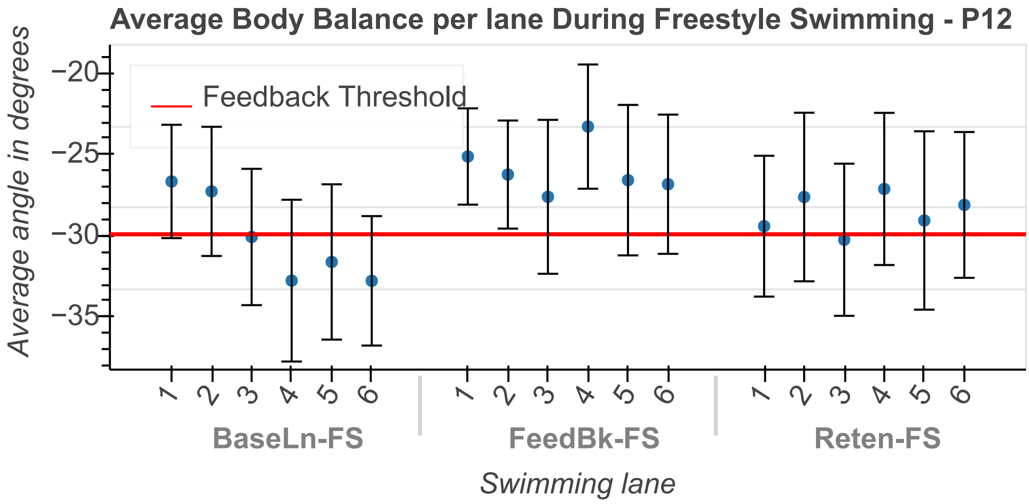

Figure D.51: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

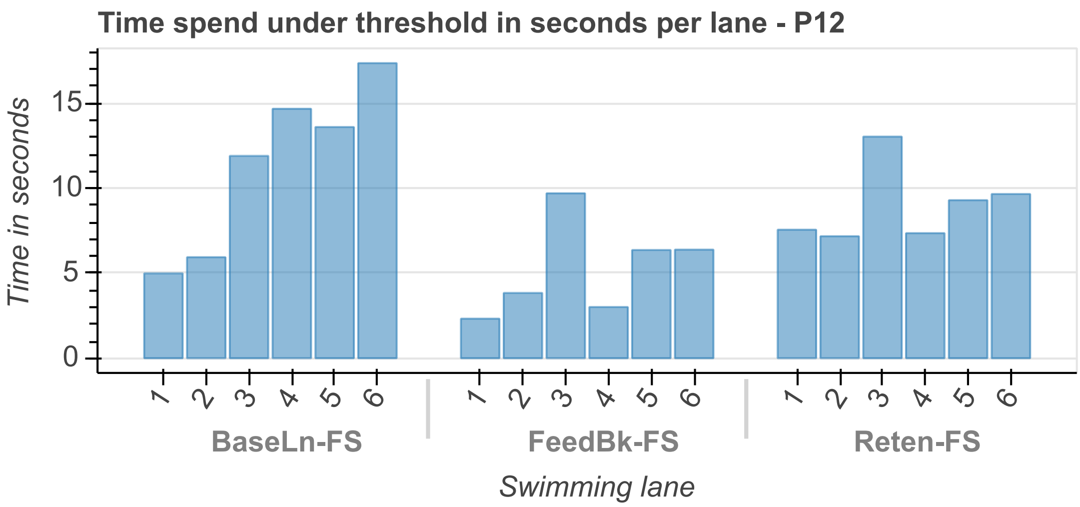

Figure D.52: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.11.2 Back Stroke Body Balance

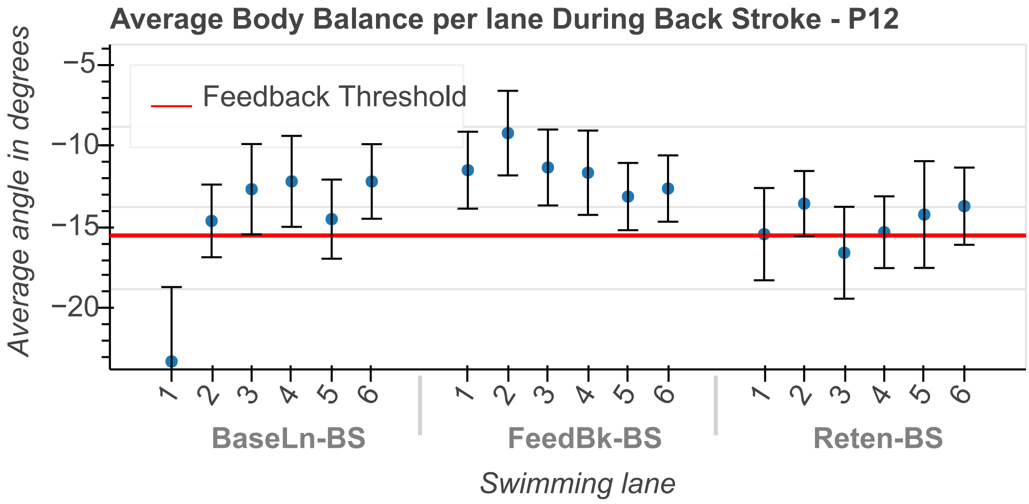

Figure D.53: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

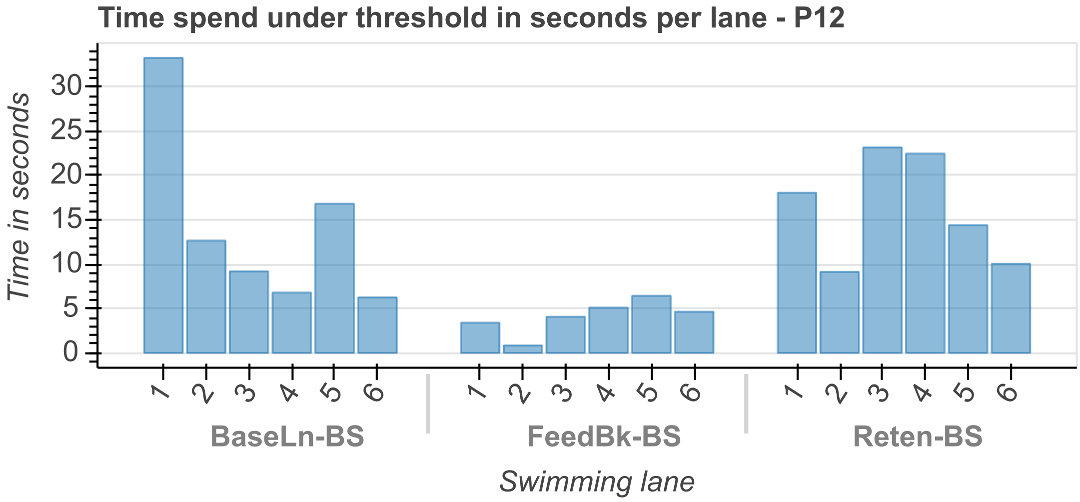

Figure D.54: Cumulative time per lane. feedback responce would be given during the FeedBk session.

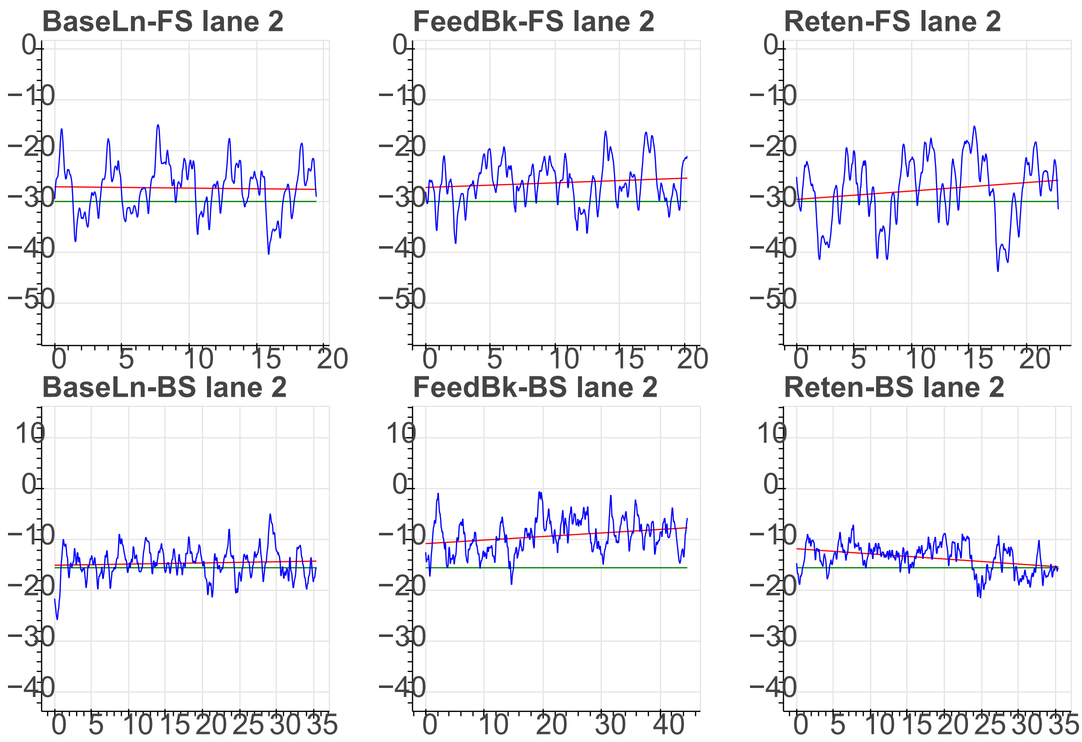

Figure D.55: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*4*	*6*	*6*	*3*	*5*	*3*
Q2	*6*	*7*	*5*	*6*	*4*	*4*
Q3	*3*	*6*	*5*	*5*	*5*	*2*
Q4	*4*	*5*	*5*	*2*	*3*	*4*
MEAN	4.25	6.0	5.25	4.0	4.25	3.25

Table D.11: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.11.3 Qualitative data

Demographics

Age: 27
Sex: male
swimming level: intermediate

Interview

I like the awareness but not my posture. I think it works better for freestyle than for back stroke. I received vibrations when I needed to, the vibrations where clear and stopped when I tried to get rid of it. The vibrations absolutly have influence on the way I was swimming. It also made me wonder what triggerd it. I think it could help me become a better swimmer. I noticed it also giving feedback when I was turning my body (sideways).

D.12 Test P13 Summary

D.12.1 FreeStyle Body Balance

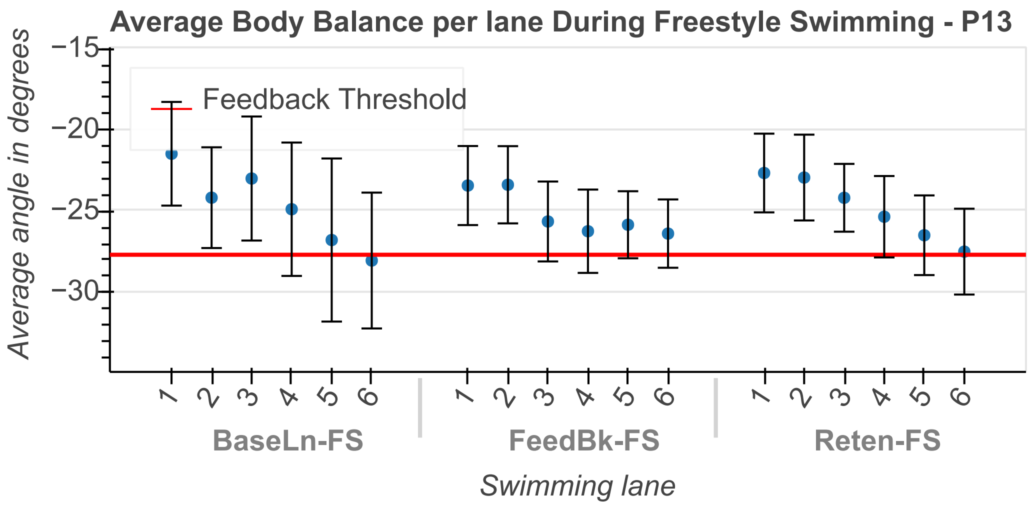

Figure D.56: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

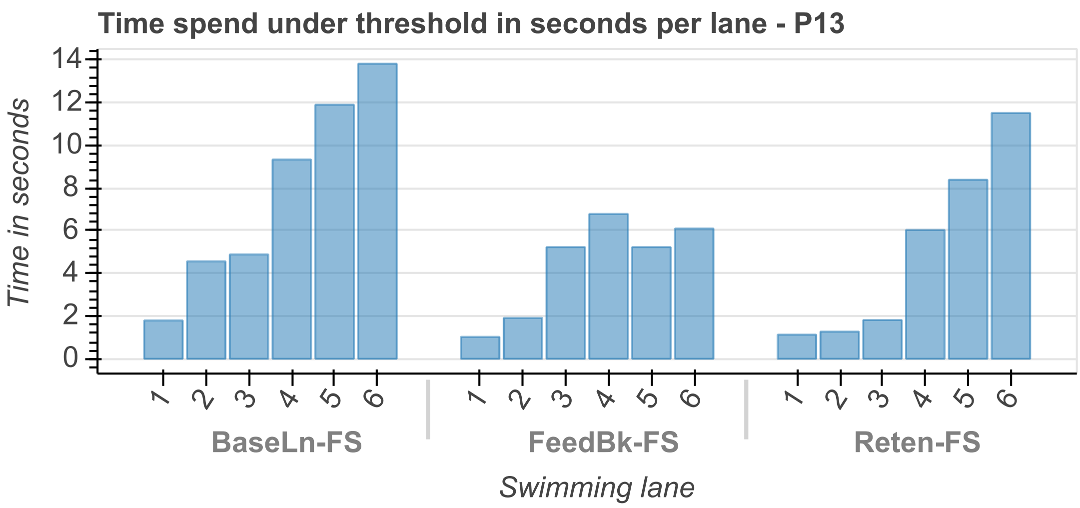

Figure D.57: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.12.2 Back Stroke Body Balance

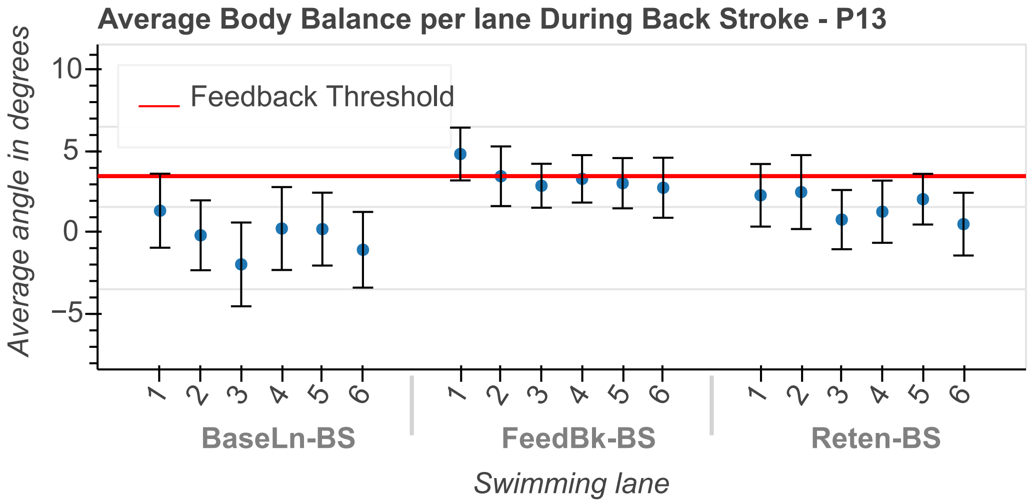

Figure D.58: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

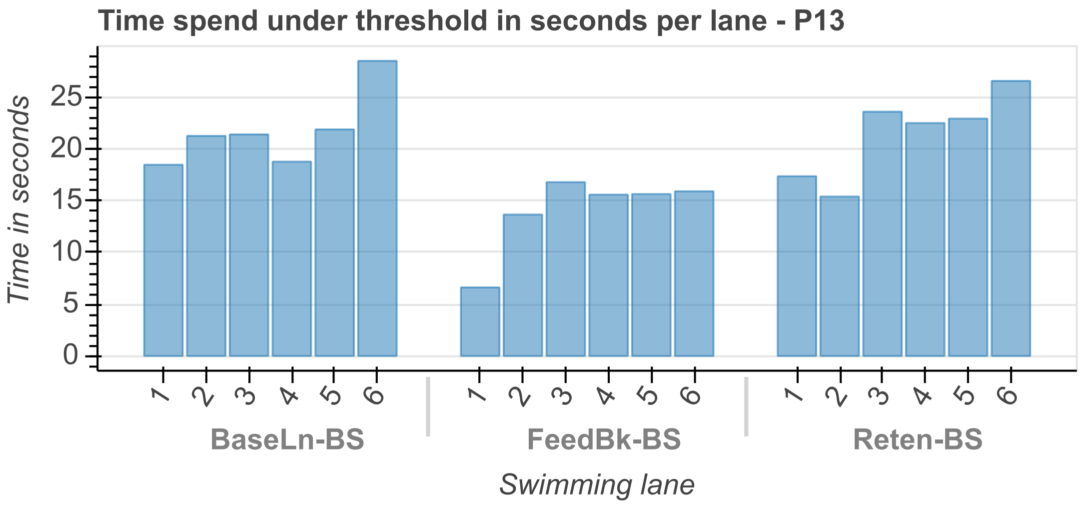

Figure D.59: Cumulative time per lane. feedback responce would be given during the FeedBk session.

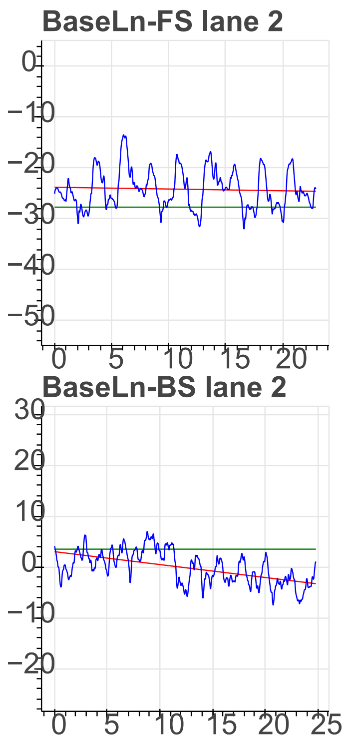

Figure D.60: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	**FeedBk_FS**	**Reten_FS**	**BaseLn_BS**	**FeedBk_BS**	**Reten_BS**
Q1	*5*	*7*	*7*	*3*	*7*	*6*
Q2	*5*	*7*	*6*	*1*	*6*	*3*
Q3	*4*	*3*	*5*	*6*	*1*	*3*
Q4	*3*	*5*	*5*	*2*	*6*	*4*
MEAN	4.25	5.5	5.75	3.0	5.0	4.0

Table D.12: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.12.3 Qualitative data

Demographics

Age: 27
Sex: male
swimming level: intermediate

Interview

I liked that there was a difference in the strength of the vibrations, that you could tell how far you are off. I think that I received vibrations when I needed. I think the feedback was clear. The feedback had most definatly influence on how I was swimming. I was activily working with the feedback. Afterwards I was swimming with the feedback still in mind, I had the feeling that I was slightly more aware about my body position. I would say this wearable could help me become a better swimmer, because I'm more aware of my bodyposition. I still think that working on technique is very important. With the freestyle I knew what to adjust but with backstroke I don't know exactly how to 'fix' my stroke.

D.13 Test P14 Summary

D.13.1 FreeStyle Body Balance

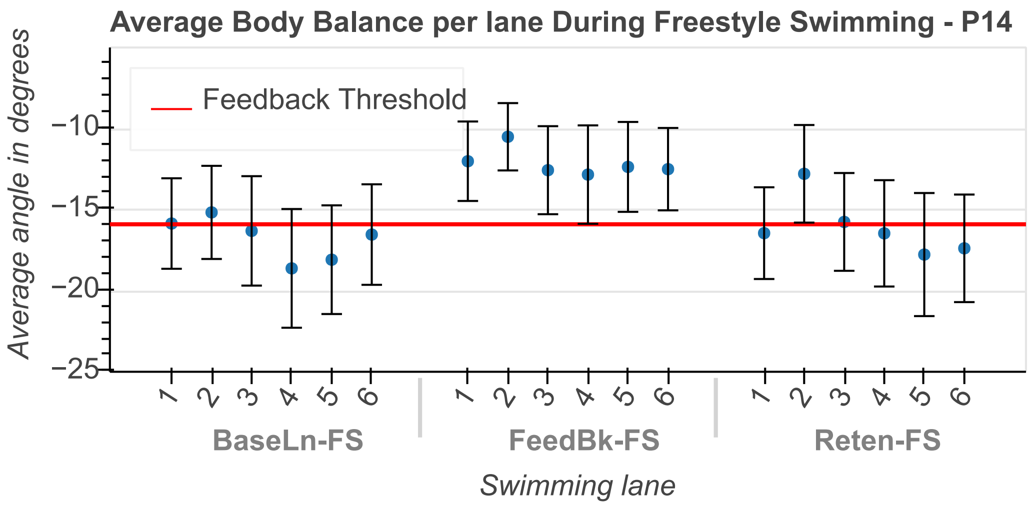

Figure D.61: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

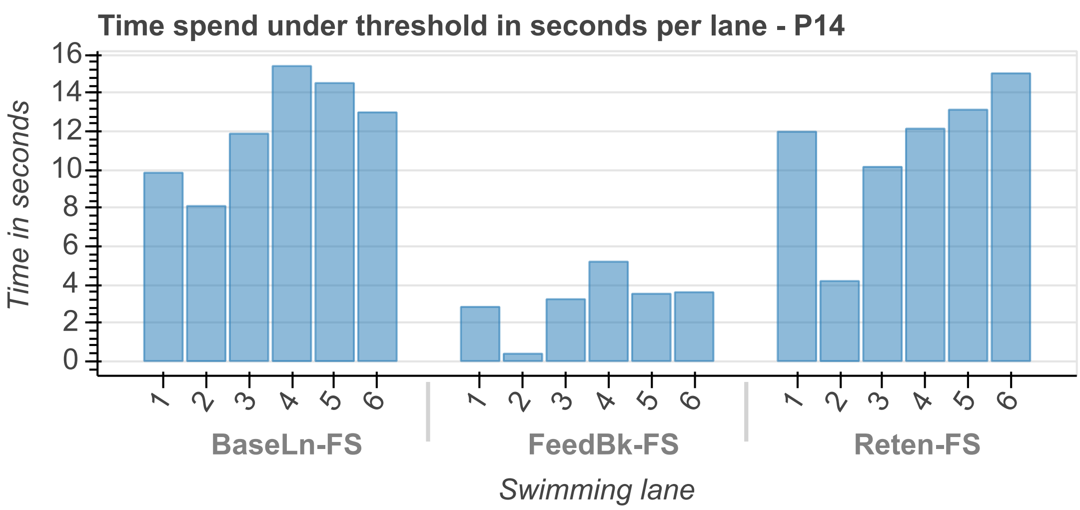

Figure D.62: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.13.2 Back Stroke Body Balance

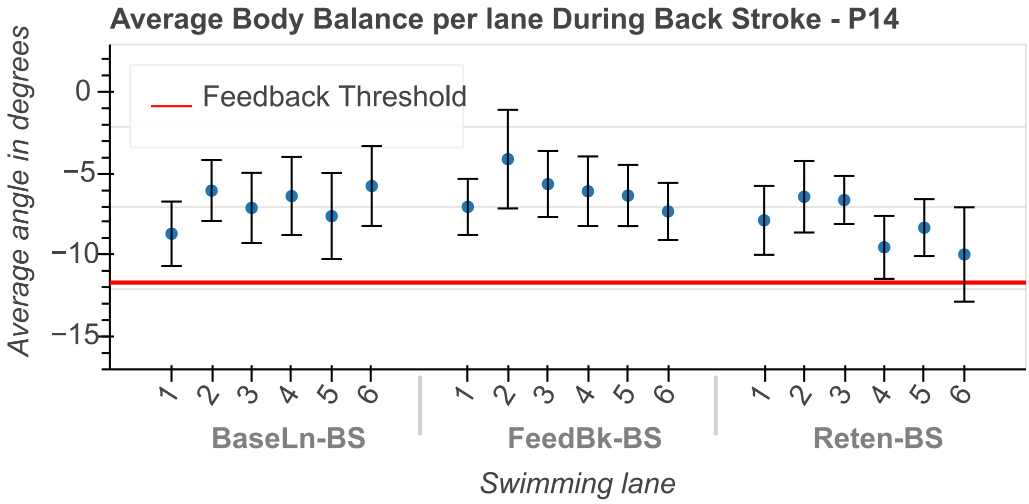

Figure D.63: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

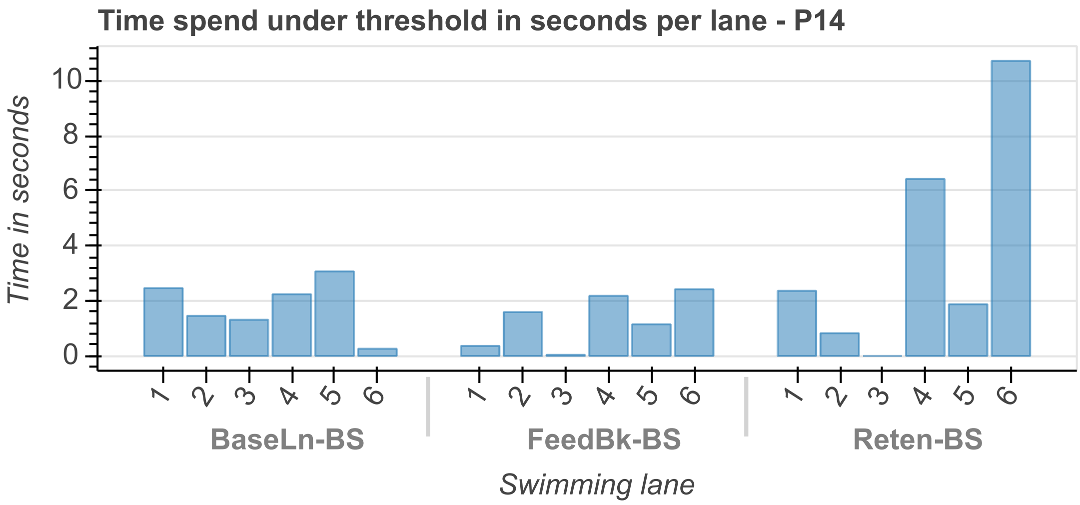

Figure D.64: Cumulative time per lane. feedback responce would be given during the FeedBk session.

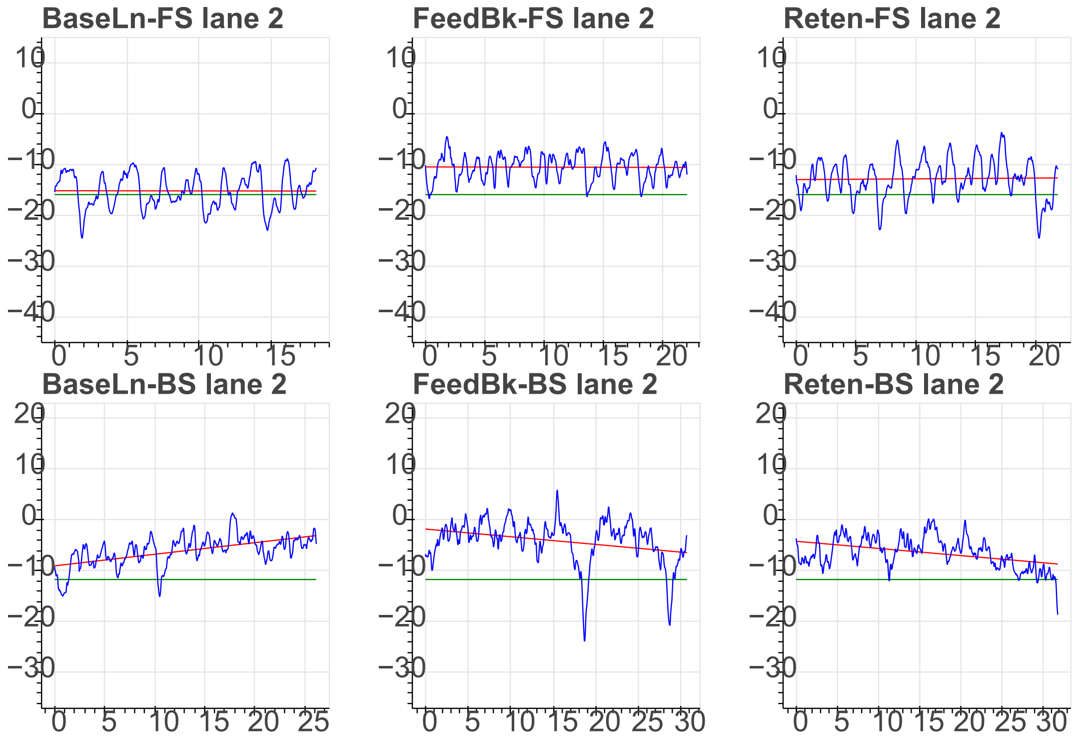

Figure D.65: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*3*	*6*	*3*	*5*	*2*	*3*
Q2	*5*	*4*	*5*	*5*	*5*	*5*
Q3	*6*	*5*	*6*	*3*	*6*	*5*
Q4	*4*	*2*	*5*	*4*	*6*	*5*
MEAN	4.5	4.25	4.75	4.25	4.75	4.5

Table D.13: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.13.3 Qualitative data

Demographics

Age: 29
Sex: male
swimming level: intermediate

Interview

When breating I know that my body is sinking and I liked the feedback at that point. I did not like receiving feedback at the turns, then it's vibrating a lot. It was clear what the vibrations meant and when I changed my position it stopt. The feedback had influence on the way I was swimming, more with freestyle than back stroke. I think this wearable could help me become a better swimmer.

D.14 Test P15 Summary

D.14.1 FreeStyle Body Balance

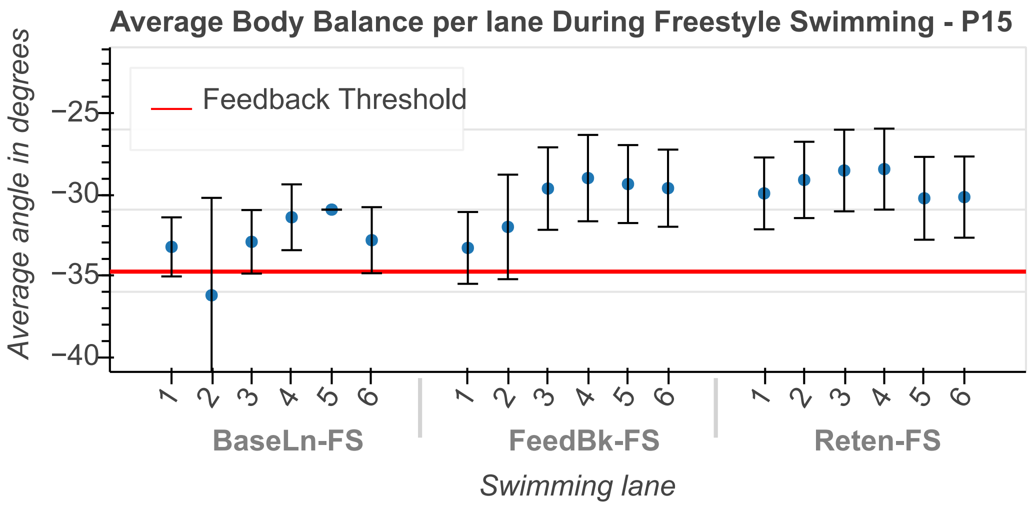

Figure D.66: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

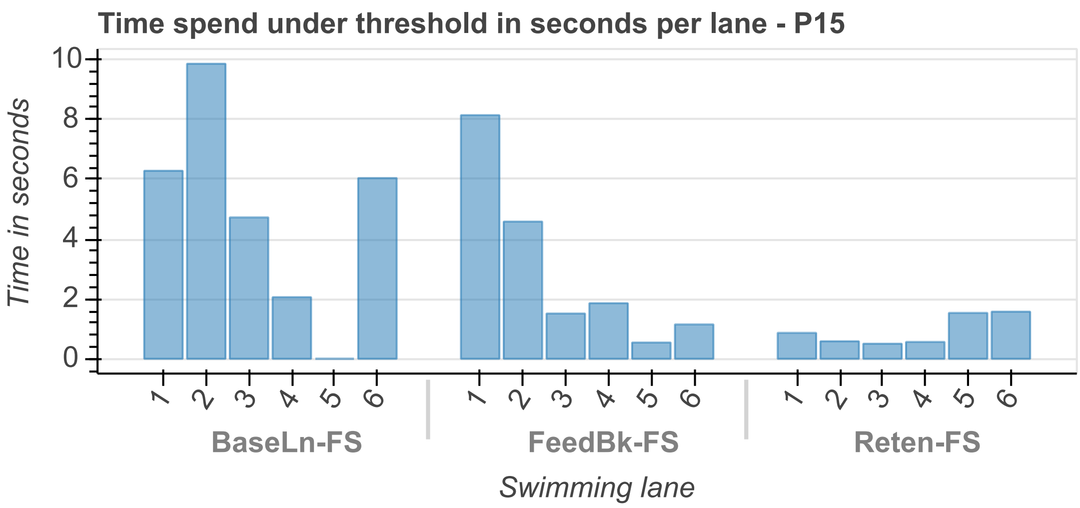

Figure D.67: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.14.2 Back Stroke Body Balance

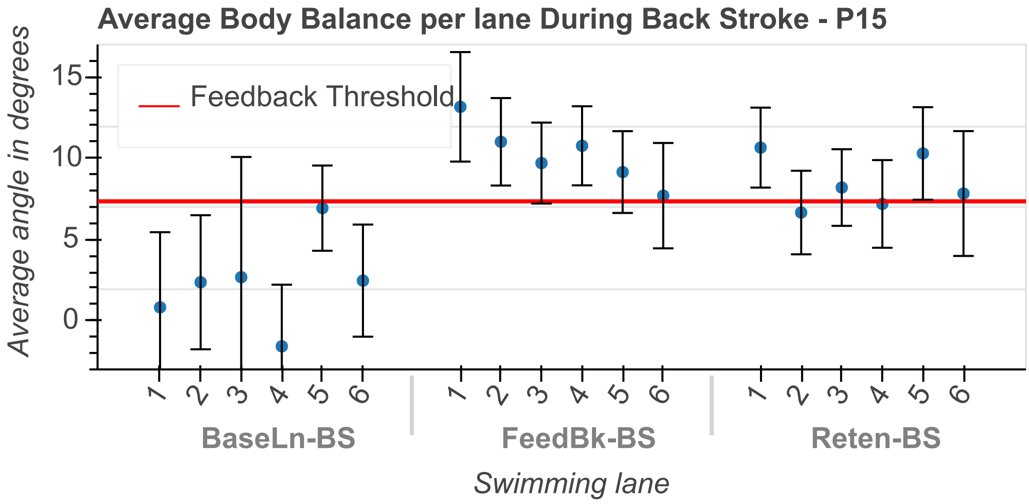

Figure D.68: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

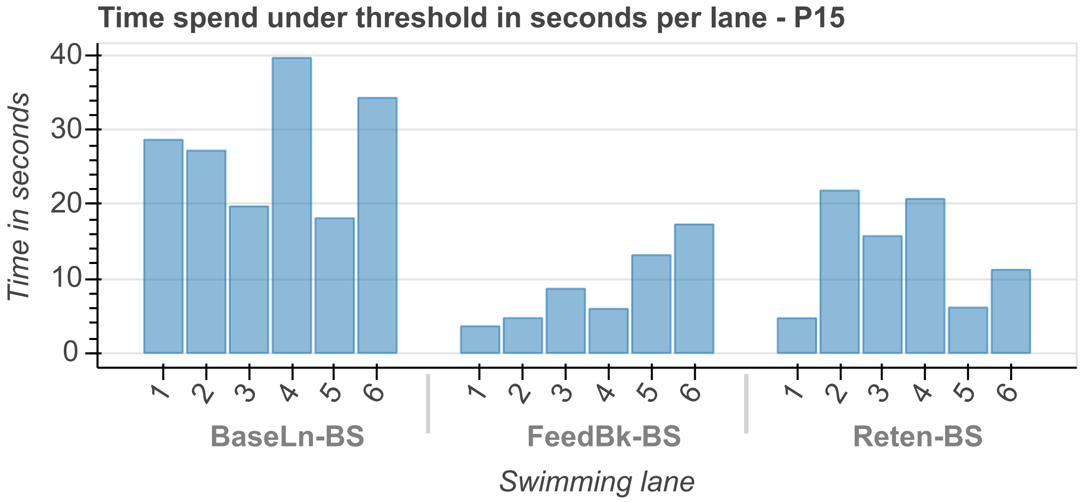

Figure D.69: Cumulative time per lane. feedback responce would be given during the FeedBk session.

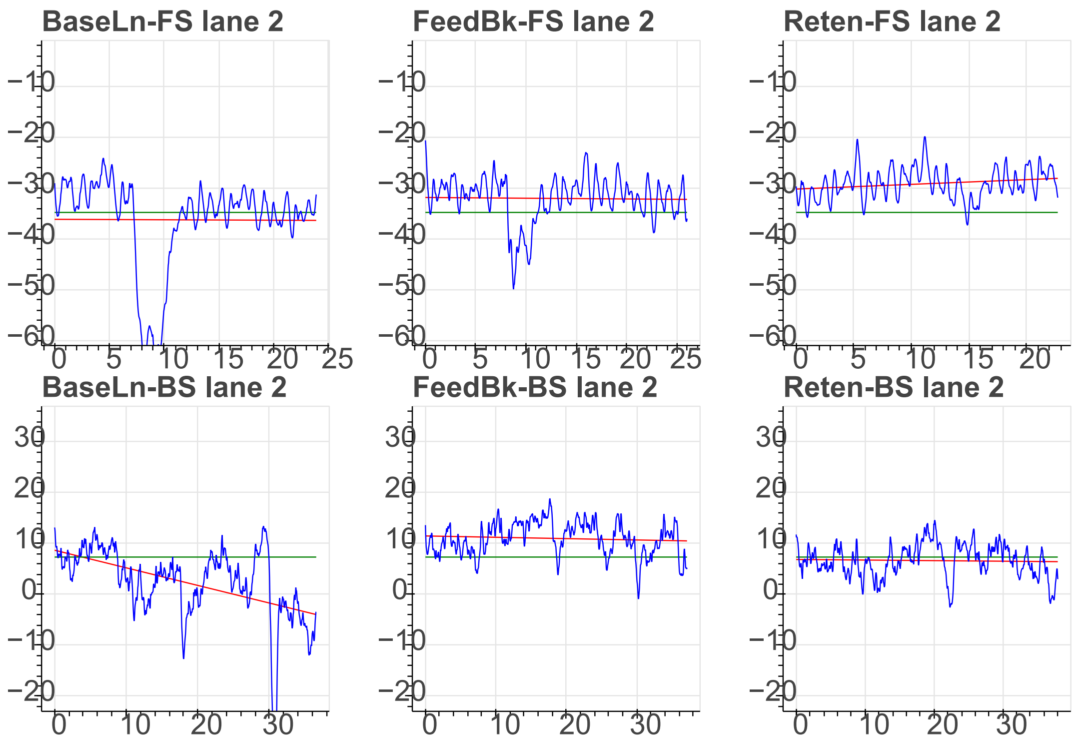

Figure D.70: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*2*	*5*	*5*	*4*	*4*	*4*
Q2	*2*	*6*	*5*	*6*	*5*	*6*
Q3	*2*	*5*	*2*	*2*	*5*	*6*
Q4	*2*	*3*	*5*	*5*	*5*	*5*
MEAN	2.0	4.75	4.25	4.25	4.75	5.25

Table D.14: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.14.3 Qualitative data

Demographics

Age: 22
Sex: female
swimming level: beginner

Interview

I liked that the wearable gave vibrations when I wasn't straight anymore, or at least what was configured. The feedback was clear. The feedback had influence on the way I swum, when I turned my head I noticed when it was too much. I think it could help me become a better swimmer.

D.15 Test P17 Summary

D.15.1 FreeStyle Body Balance

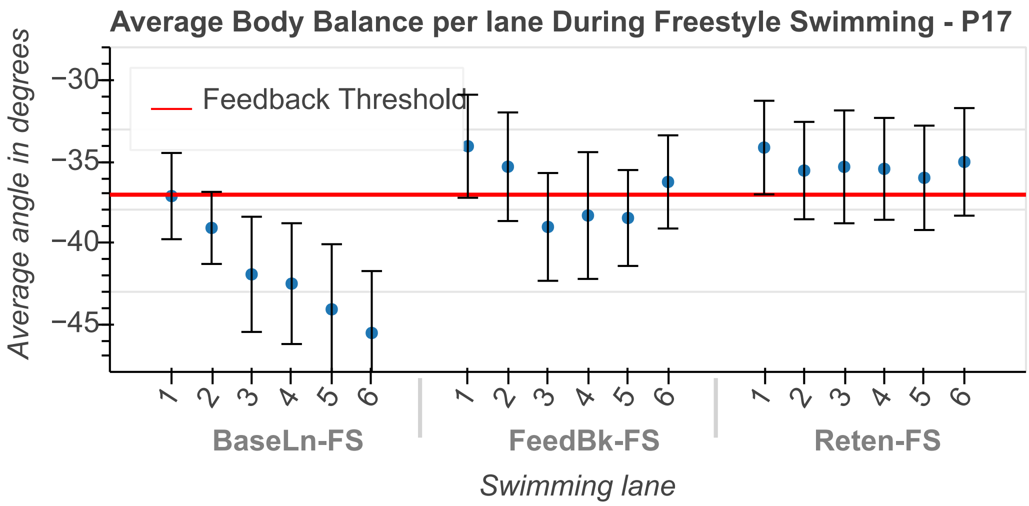

Figure D.71: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

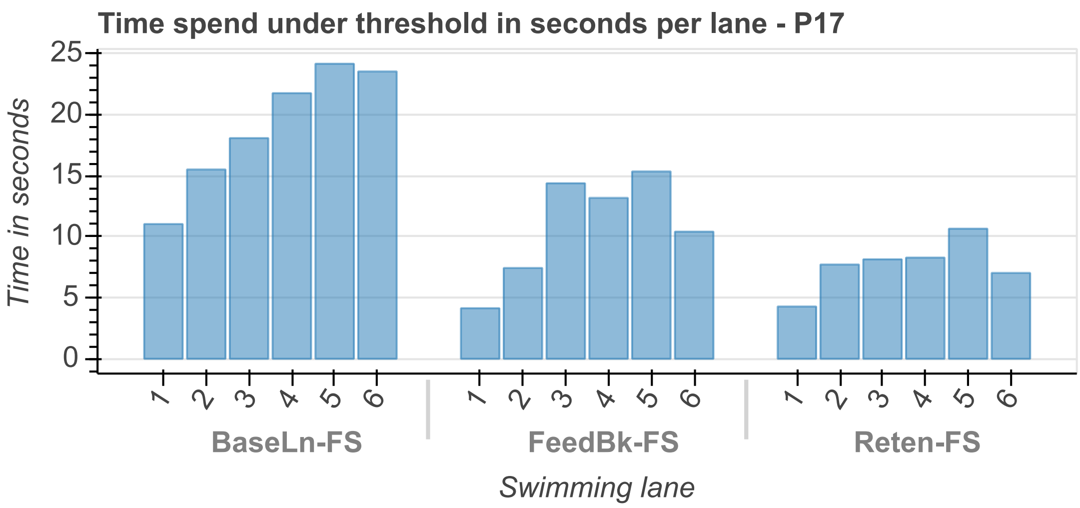

Figure D.72: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.15.2 Back Stroke Body Balance

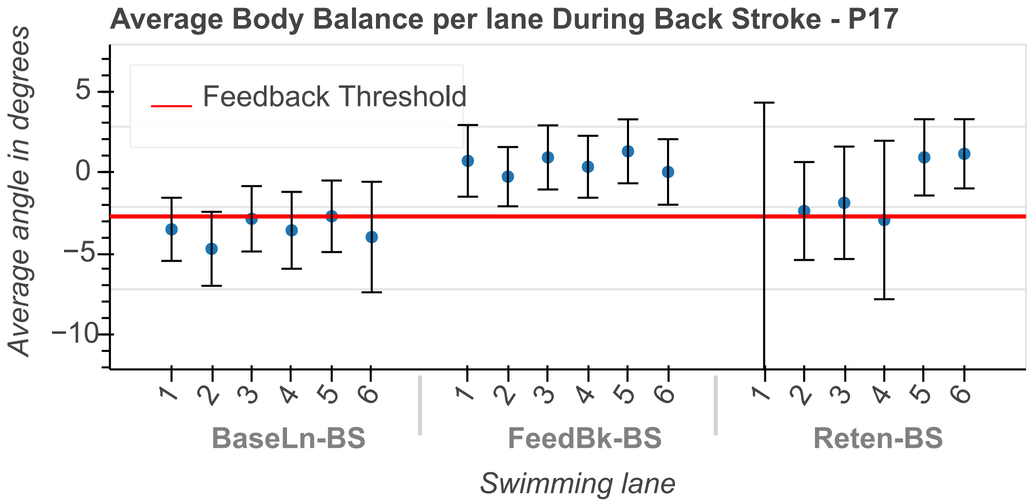

Figure D.73: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

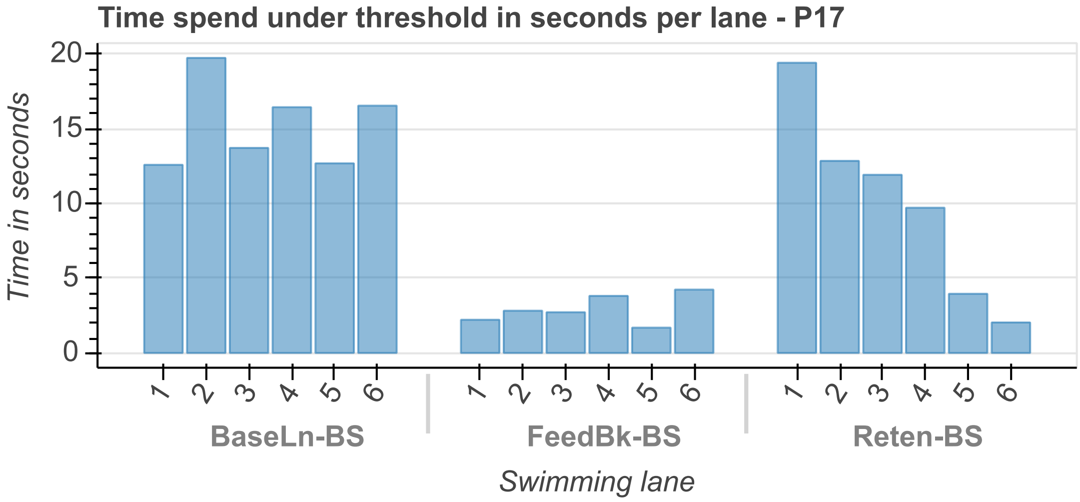

Figure D.74: Cumulative time per lane. feedback responce would be given during the FeedBk session.

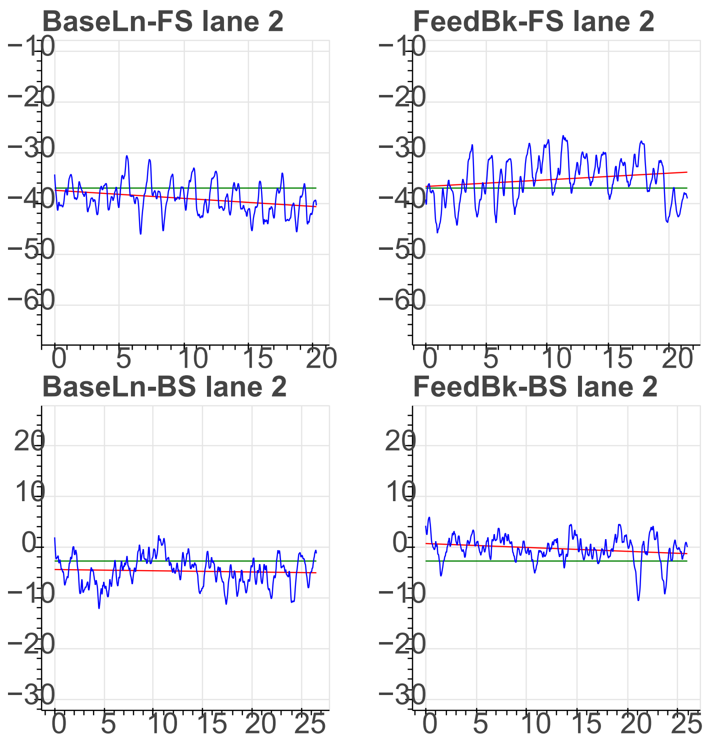

Figure D.75: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*5*	*7*	*6*	*4*	*6*	*5*
Q2	*5*	*7*	*6*	*5*	*6*	*5*
Q3	*5*	*6*	*6*	*5*	*6*	*5*
Q4	*2*	*6*	*6*	*3*	*6*	*6*
MEAN	4.25	6.5	6.0	4.25	6.0	5.25

Table D.15: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.15.3 Qualitative data

Demographics

Age: 21
Sex: male
swimming level: intermediate

Interview

I liked the vibrating feedback a lot because I noticed when my legs where too low, it helped a lot. It was sometimes unclear with freestyle what the vibration meant, because it went of after two lanes a bit too much, so I had to figure it out, but in the end it was all clear. I received vibrations when I needed to receive vibrations. I noticed on the last run that I actively also changed my posture based on previous run with feedback. I think it could help me become a better swimmer till a certain level at some points you probably need other forms of feedback. I noticed I got feedback with breathing, so I know I have to spend less time on that.

D.16 Test P18 Summary

D.16.1 FreeStyle Body Balance

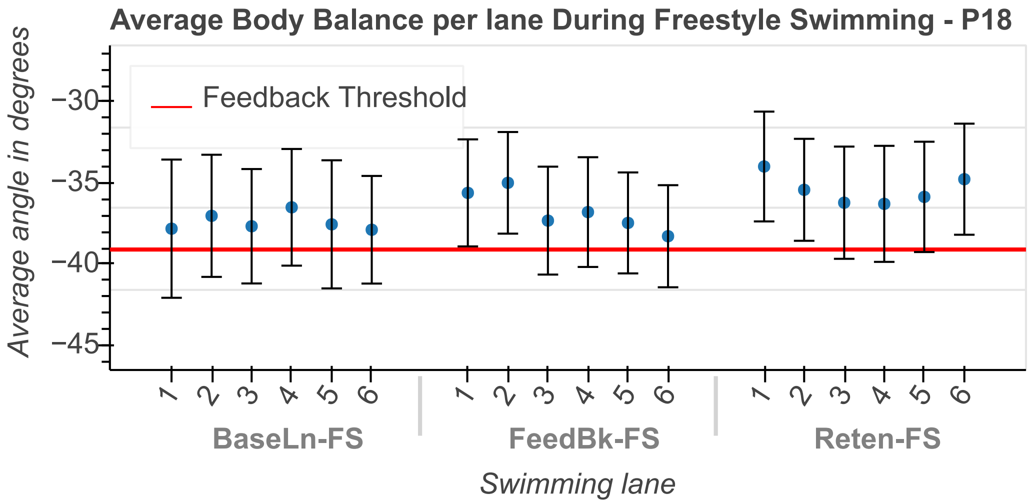

Figure D.76: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

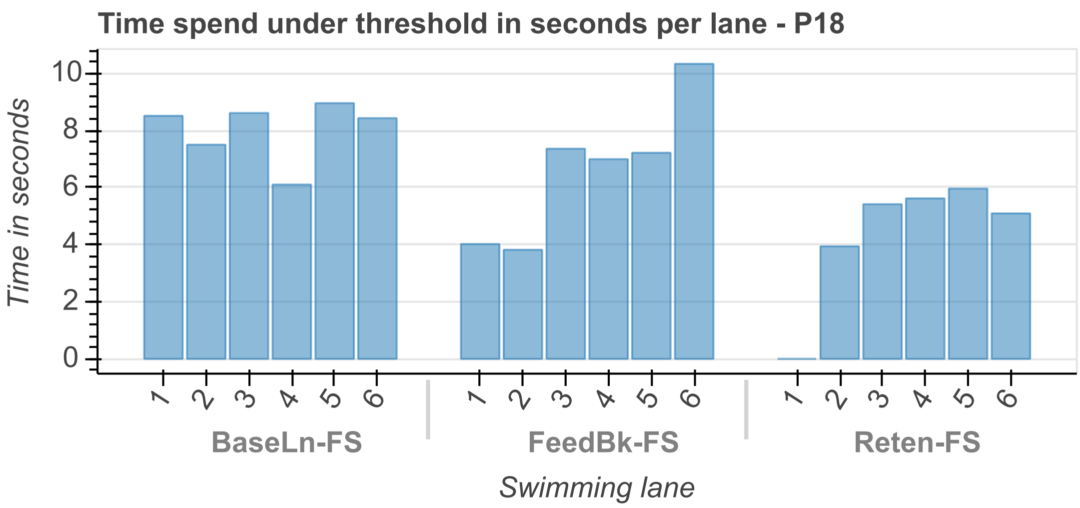

Figure D.77: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.16.2 Back Stroke Body Balance

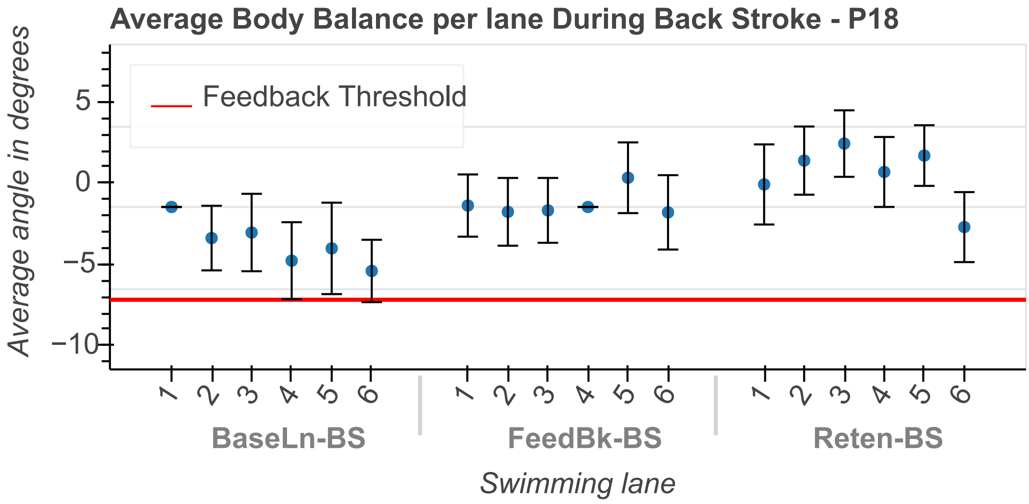

Figure D.78: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

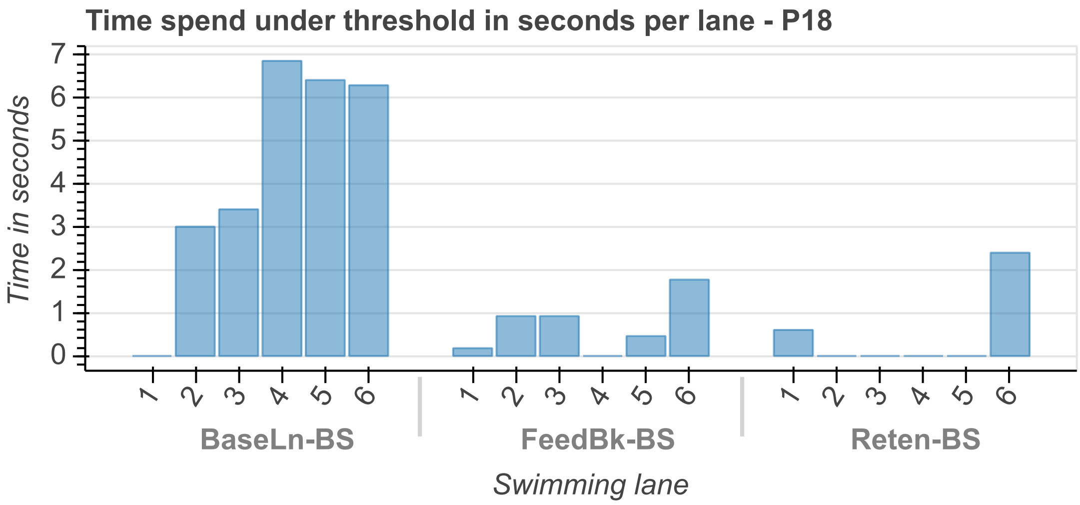

Figure D.79: Cumulative time per lane. feedback responce would be given during the FeedBk session.

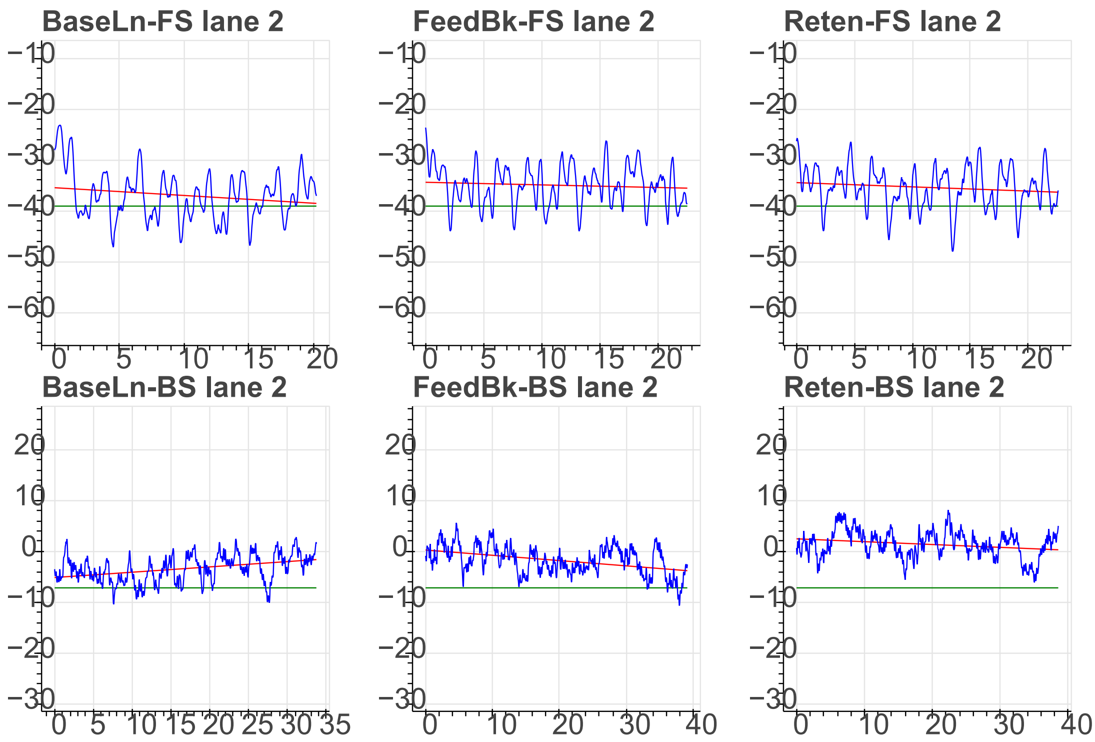

Figure D.80: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*4*	*5*	*4*	*5*	*5*	*4*
Q2	*4*	*5*	*4*	*5*	*6*	*3*
Q3	*5*	*5*	*3*	*2*	*5*	*3*
Q4	*2*	*6*	*3*	*5*	*5*	*4*
MEAN	3.75	5.25	3.5	4.25	5.25	3.5

Table D.16: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.16.3 Qualitative data

Demographics

Age: 28
Sex: male
swimming level: beginner

Interview

I liked the feedback, it was sufficiently noticeable, it didn't hurt, it didn't tickle. It might have been slightly erotic, if you put it in the right place. It was clear what the feedback meant, you notice that the device kicks in when you did something wrong, it was immediately obvious what was happening. I'm not always sure when I do something wrong, but the device helps me remind me to adjust my posture. I think you shouldn't be reliant on the device, but in the beginning phase it can help to build good habits. So yeah, for beginners like me it's very helpful. I think

more can be done with the device, but the device worked, it was simple, intuitive and it did what it had to do.
I had cramps, especially after backstroke but it shouldn't influence the test. I noticed getting fatigued after 4 or 5 lanes of backstroke and you might see this in the data.

D.17 Test P19 Summary

D.17.1 FreeStyle Body Balance

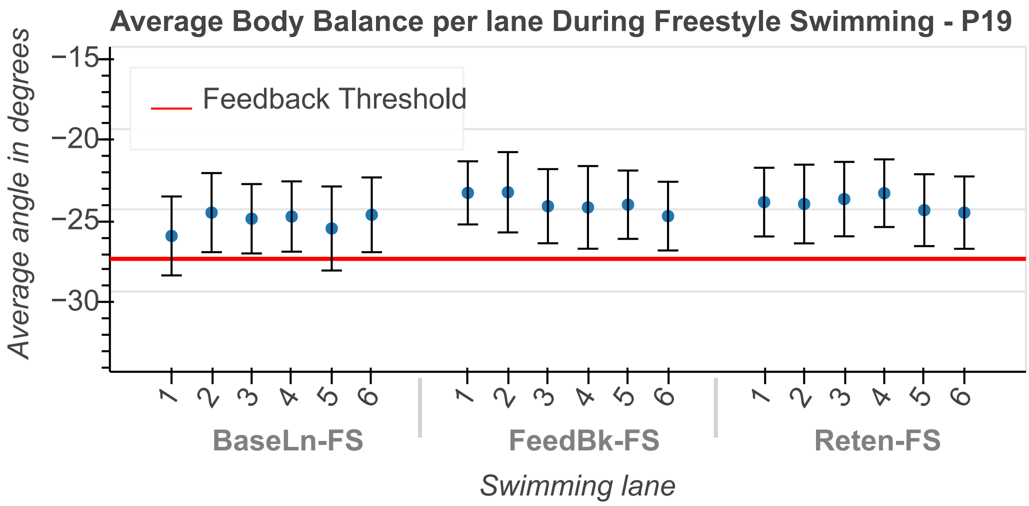

Figure D.81: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

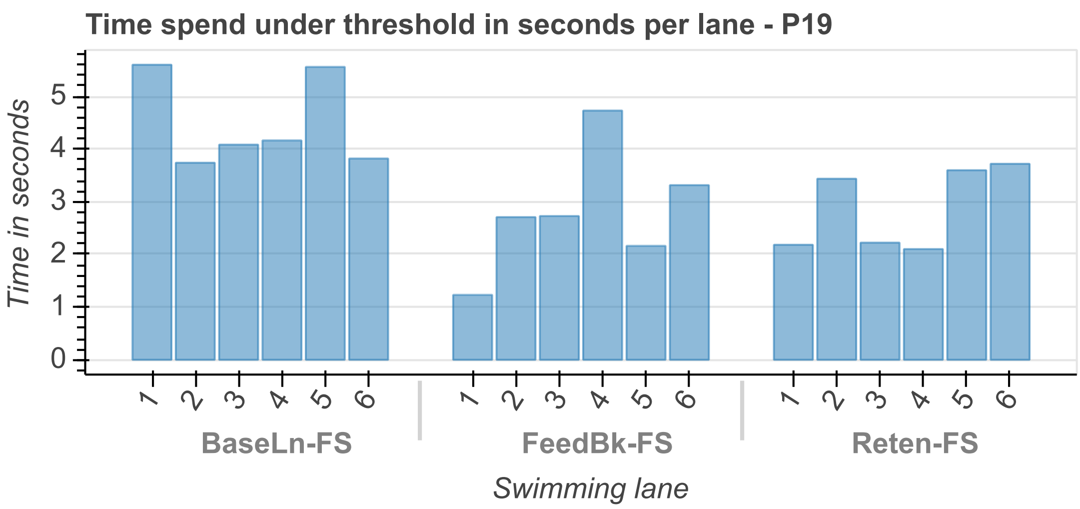

Figure D.82: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.17.2 Back Stroke Body Balance

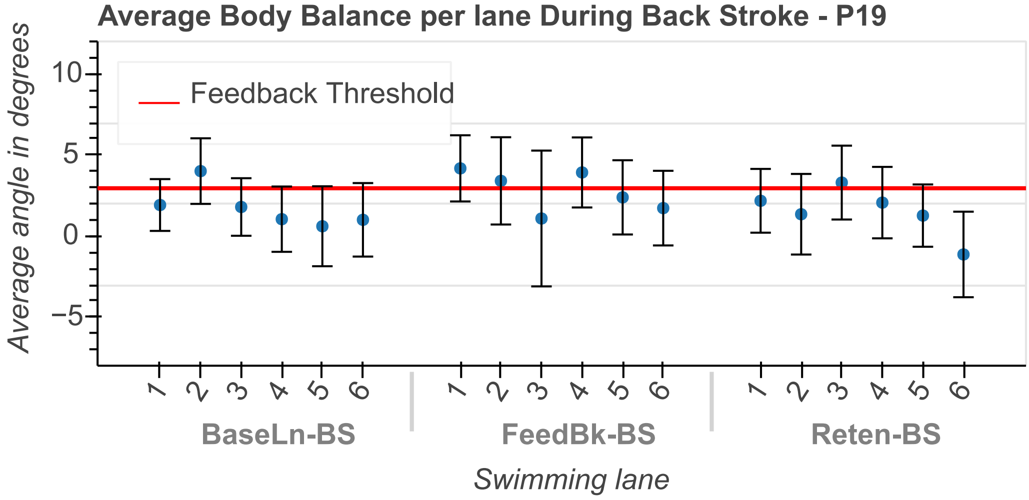

Figure D.83: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

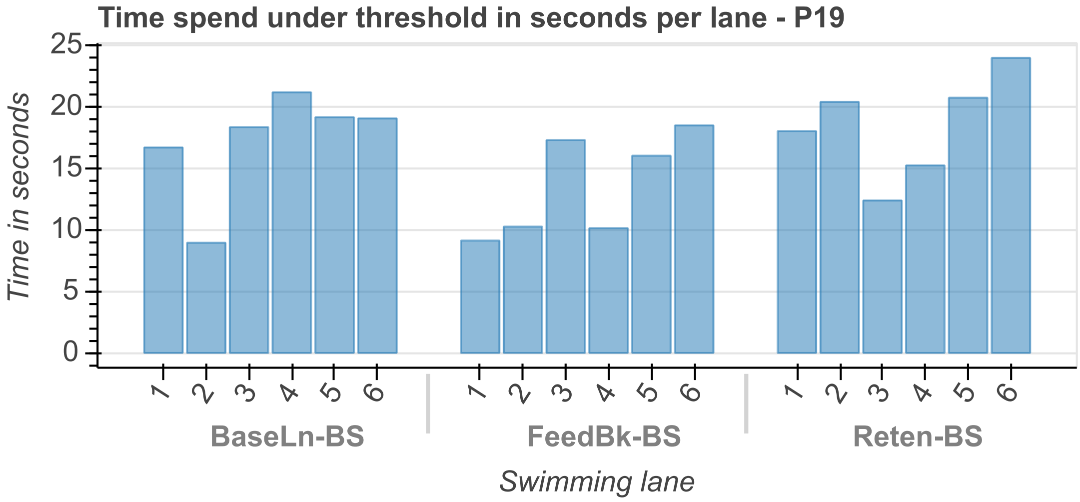

Figure D.84: Cumulative time per lane. feedback responce would be given during the FeedBk session.

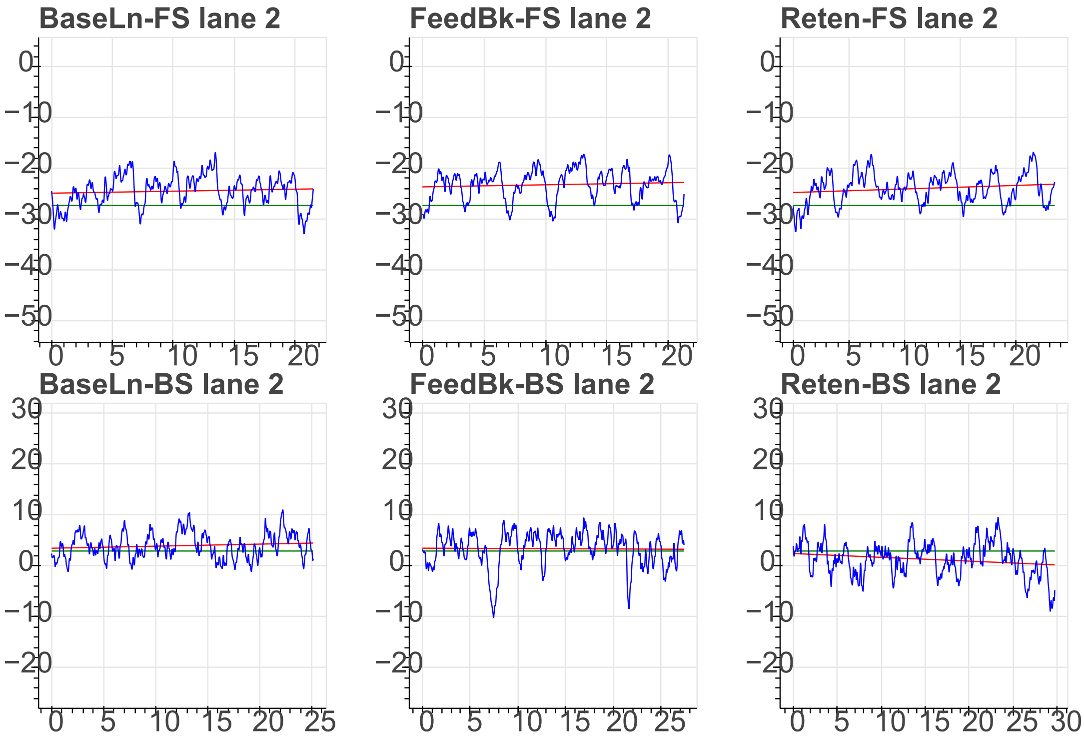

Figure D.85: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*5*	*6*	*7*	*5*	*7*	*7*
Q2	*5*	*7*	*6*	*5*	*6*	*6*
Q3	*4*	*5*	*7*	*3*	*6*	*7*
Q4	*3*	*6*	*6*	*5*	*6*	*6*
MEAN	4.25	6.0	6.5	4.5	6.25	6.5

Table D.17: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.17.3 Qualitative data

Demographics

Age: 19
Sex: female
swimming level: intermediate

Interview

I liked that I knew when my bodyposition was not right so I could adjust it and keep my body more straight. I was clear what the feedback meant. I received vibrations when I needed to receive vibrations. The feedback had influence on the way I was swimming, because the second time I swam without feedback I adjusted my body more so I kept my body more straight. I think it could help me become a better swimmer but for backstroke I also need to learn how I keep my position in the lane. I noticed the second time I kept my body straight and I was more attentive on my posture.

D.18 Test P20 Summary

D.18.1 FreeStyle Body Balance

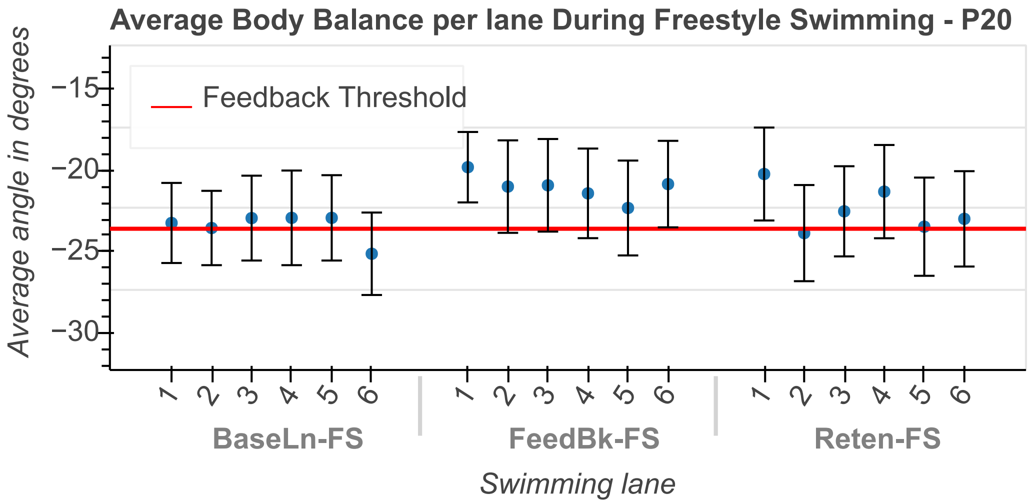

Figure D.86: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

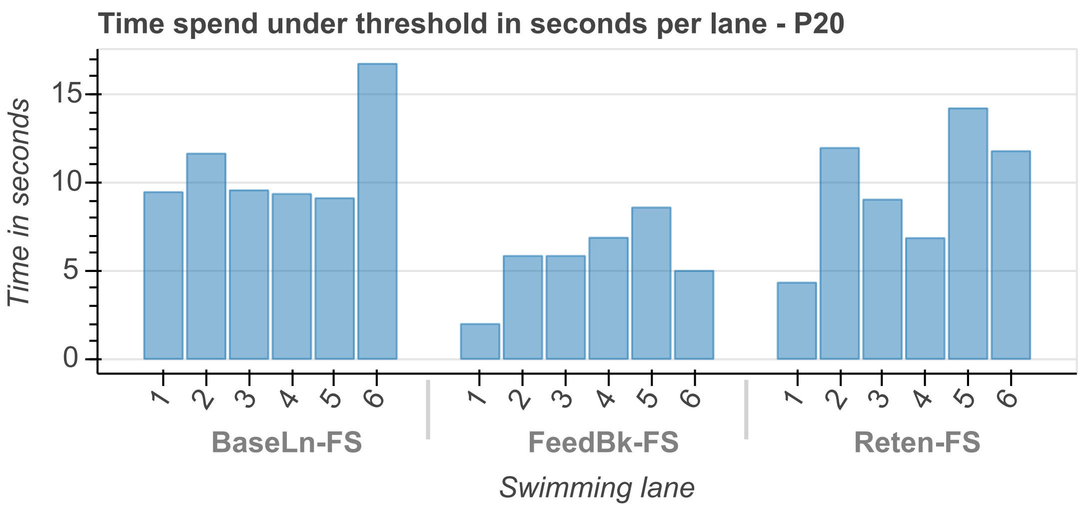

Figure D.87: Cumulative time per lane. feedback responce would be given during the FeedBk session.

D.18.2 Back Stroke Body Balance

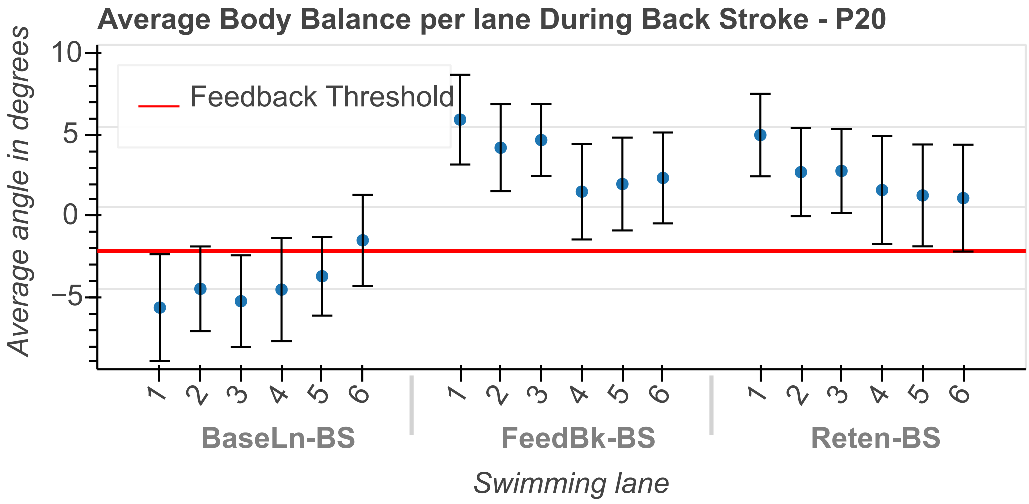

Figure D.88: The whiskers show the RMS of the residuals of a linear regression done for the respective lane. Angles below the threshold cause the would elicit a haptic feedback response.

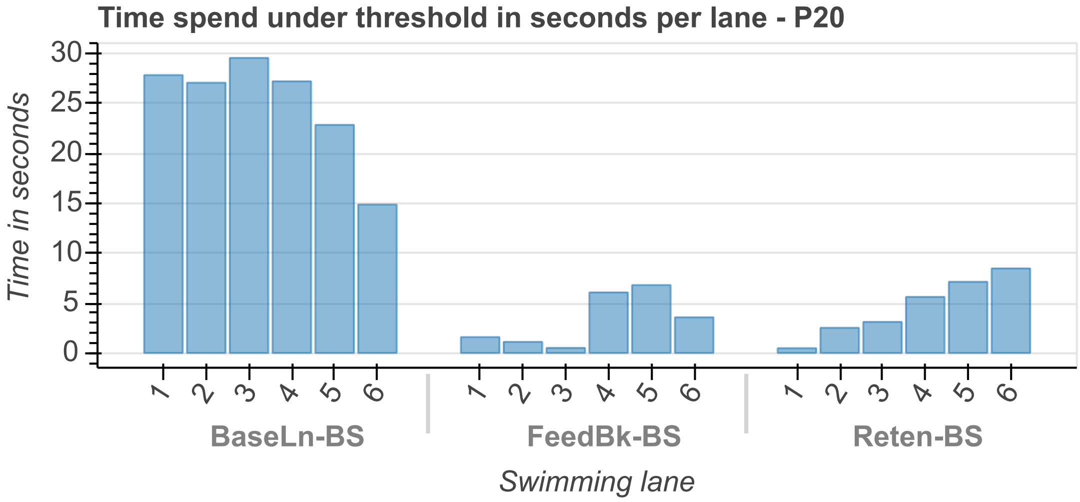

Figure D.89: Cumulative time per lane. feedback responce would be given during the FeedBk session.

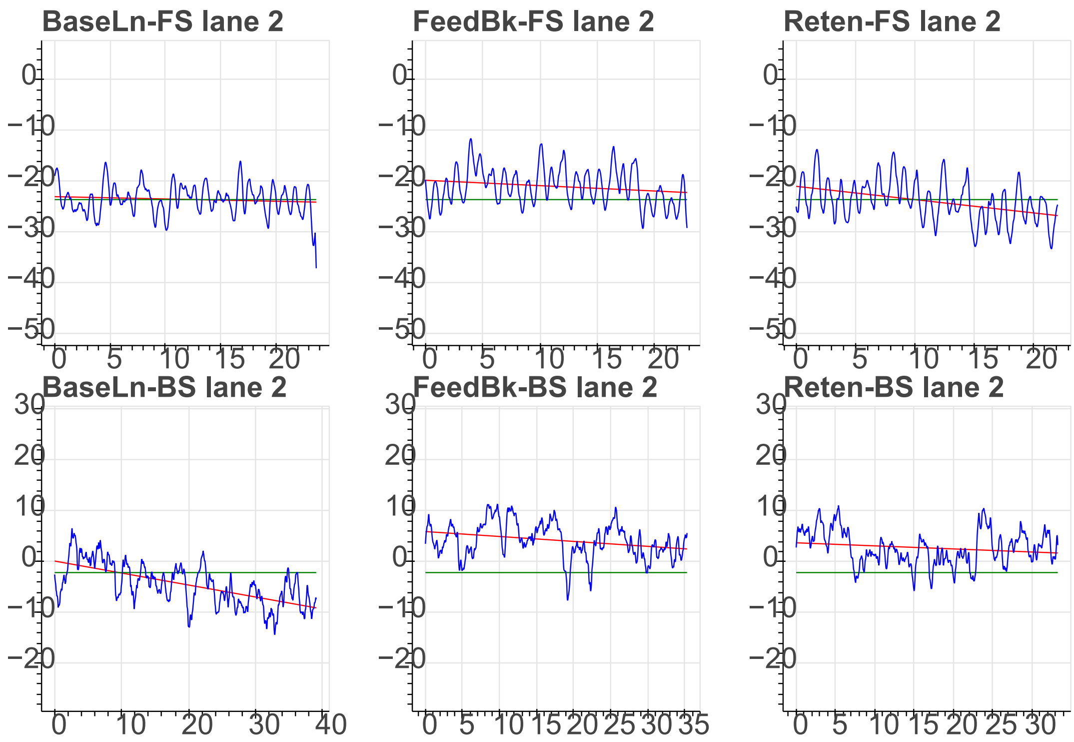

Figure D.90: Examples of the calculated angle for a specific lane. The blue line stands for the angle over time, the red line shows the linear regression of the blue line, and the green line denotes the threshold value for the specific swim stroke for that participant.

	BaseLn_FS	FeedBk_FS	Reten_FS	BaseLn_BS	FeedBk_BS	Reten_BS
Q1	*5*	*6*	*5*	*5*	*6*	*6*
Q2	*5*	*5*	*4*	*5*	*5*	*5*
Q3	*2*	*5*	*5*	*4*	*5*	*5*
Q4	*3*	*5*	*4*	*4*	*5*	*4*
MEAN	3.75	5.25	4.5	4.5	5.25	5.0

Table D.18: Table shows a measure of the body balance awareness over during the different swimming tests. The values of Q3 are inverted.

D.18.3 Qualitative data

Demographics

Age: 29
Sex: female
swimming level: intermediate

Interview

I liked the feedback when doing backstroke, with freestyle it was a bit more difficult to determine what to do. It remembers you about your posture. Feedback during freestyle was a bit more often and I couldn't always solve it. For the backstroke it was clear and I recieved it on the right moment, witht freestyle I wasn't always sure. The feedback had influence on my swimming because I was very aware of my posture, but maybe also the experiment in general, makes you aware of your posture. I think it has the potential to help me become a better swimmer.

E SWIMMING TRACKER TABLE

Table E.1: Table adapted from [1], includes an overview of information from papers about inertial measurement units used in swimming.

Ref.	Year	Participants			Swim Strokes				Sensor Range		Size & Mass	Volume	Sample Rate
		E	C	R	Fc	Br	Bk	Bf	Accel. (m·s-2)	Gyro. (rad·s−1)	Size (m × 10-3) Mass (kg × 10-3)	(m3)	(Hz)
[15]	2000	-	2	-	•				±490.5	N/A	Unrep 62	Unrep	Unrep
[16]	2002	-	5	-	•	•			±98.1	±26.2	142.8 × 23 78	Unrep	128
[17]	2002	-	5	-	•				±98.1	N/A	88 × 21 50	Unrep	128
[12]	2003	-	2	-		•			± 490.5	N/A	Unrep 62	Unrep	Unrep
[18]	2004	-	1	-	•	•	•	•	±19.62	N/A	Unrep Unrep	Unrep	150
[19]	2004	6	-	-	•				Unrep	Unrep	Unrep Unrep	Unrep	250
[20]	2004	-	5	-	•	•	•	•	±98.1	±26.2	142 × 23 78	Unrep	128
[21]	2005	-	1	-	•				±19.6	N/A	Unrep Unrep	Unrep	150

[22]	2006	-	4	-	•				±98.1	N/A	88 × 21 50	Unrep	128
[23]	2007	-	-	-	•	•	•	•	N/A	N/A	Unrep Unrep	Unrep	32
[24]	2007	-	-	-	-	-	-	-	Unrep	N/A	Unrep Unrep	Unrep	Unrep
[25]	2008	-	4	4	•				Unrep	N/A	Unrep Unrep	Unrep	256
[26]	2008	1	-	3				•	±14.7–±58.9	N/A	Unrep Unrep	Unrep	200
[11]	2008	6	-	-	•	•	•	•	±19.6	N/A	Unrep Unrep	Unrep	150
[27]	2008	-	2	-	•	•		•	±19.6	±2.6	52 × 34 × 12 22	2.12 × 10−5	150
[28]	2008	-	-	-	•	•	•	•	Unrep	N/A	Unrep Unrep	Unrep	100
[29]	2008	-	1	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[30]	2009	-	1	-	•				Unrep	N/A	36 × 42 × 12 34	5.14 × 10−5	256
[31]	2009	7	-	15	•				±29.4	N/A	36 × 42 × 12 34	5.14 × 10−5	256
[32]	2009	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[33]	2009	12	-	-	•				±19.6	>600	52 × 33 × 11 20.7	1.89 × 10−5	100
[34]	2009	14	-	-	•				±19.6	>600	52 × 33 × 11 20.7	1.89 × 10−5	100
[35]	2009	-	1	-	•				Unrep	N/A	Unrep Unrep	Unrep	128
[36]	2009	-	-	-	•				Unrep	Unrep	Unrep Unrep	Unrep	Unrep

[37]	2009	-	-	-	•	•	•	•	Unrep	N/A	Unrep Unrep	Unrep	Unrep
[38]	2010	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	30
[39]	2010	-	-	-	•	•	•		Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[40]	2010	-	1	-	•	•	•	•	±29.4	±8.7	150 × 90 Unrep	Unrep	50
[41]	2010	-	1	-	•				±29.4	±8.7	150 × 90 Unrep	Unrep	50
[42]	2010	-	-	-	•				Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[43]	2010	-	-	1	•	•			Unrep	Unrep	Unrep Unrep	Unrep	190
[44]	2010	-	-	1	•	•	•		Unrep	N/A	Unrep 7	Unrep	Unrep
[45]	2010	-	1	-	•				±29.4	±8.7	150 × 90 Unrep	Unrep	50
[46]	2010	3	-	-	•	•	•	•	Unrep	N/A	Unrep Unrep	Unrep	100
[47]	2010	8	-	-	•	•	•	•	Unrep	Unrep	88 × 51 × 25 93	1.1 × 10−4 Unrep	100
[48]	2010	-	53	-	•				Unrep	N/A	Unrep Unrep	Unrep	Unrep
[49]	2010	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[50]	2011	-	1	-				•	±14.7–±58.9	Unrep	Unrep Unrep	Unrep	200
[51]	2011	12	-	-	•				±19.6	>600	52 × 33 × 11 20.7	1.89 × 10−5	100
[52]	2011	-	-	1	•				Unrep	N/A	Unrep Unrep	Unrep	50

[53]	2011	1	-	-	•				±78.5	±26.2	52 × 33 × 10 20	1.72 × 10−5	100
[54]	2011	-	-	-	•				Unrep	Unrep	Unrep Unrep	Unrep	100
[55]	2011	-	-	6	•				Unrep	Unrep	Unrep Unrep	Unrep	200
[56]	2011	2	-	-	•				±78.5	±26.2	52 × 33 × 10 20	1.72 × 10−5	100
[57]	2011	-	2	-	•	•	•	•	±29.4	±8.7	150 × 90 Unrep	Unrep	50
[58]	2011	-	-	-	•	•	•		Unrep	N/A	Unrep 18	Unrep	50
[59]	2011	-	11	-	•	•	•		Unrep	N/A	Unrep Unrep	Unrep	50
[60]	2011	-	1	-	•	•		•	Unrep	Unrep	57 × 91 × 24 65.6	1.24 × 10−4	50
[61]	2011	-	-	1	•				±78.5	±26.2	53 × 33 × 10 20	1.75 × 10−5	100
[62]	2012	7	-	11	•				±29.4	N/A	36 × 42 × 12 34	1.81 × 10−5	256
[63]	2012	12	-	-	•				±19.6	>600	52 × 33 × 11 20.7	1.89 × 10−5	100
[64]	2012	11	-	19	•				±107.9	±15.7	Unrep Unrep	Unrep	500
[65]	2012	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[66]	2012	-	-	-	•	•	•	•	Unrep	N/A	Unrep Unrep	Unrep	Unrep
[67]	2012	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[68]	2012	-	1	-	•				±29.4	±8.7	150 × 90 Unrep	Unrep	50

[69]	2012	1	-	-	•				±29.4	±8.7	150 × 90 Unrep	Unrep	50
[70]	2012	9	-	-	•				±78.5	±26.2	52 × 33 × 10 20	1.72 × 10−5	100
[71]	2013	-	2	-	•	•	•	•	±29.4	±8.7	150 × 90 Unrep	Unrep	50
[72]	2013	-	20	-	•				±107.9	±15.7	50 × 40 × 16 36	3.2 × 10−5	500
[73]	2013	-	6	6	•				±107.9	±15.7	50 × 40 × 16 36	3.2 × 10−5	500
[74]	2013	-	7	-		•			±98.1	±15.7	50 × 40 × 16 36	3.2 × 10−5	100
[75]	2013	-	-	1	•	•	•	•	Unrep	N/A	Unrep Unrep	Unrep	50
[76]	2013	-	-	1	•				Unrep	N/A	Unrep Unrep	Unrep	50
[77]	2013	-	-	1	•	•	•	•	Unrep	N/A	Unrep Unrep	Unrep	50
[78]	2013	-	12	-	•	•	•	•	±14.7	±8.7	Unrep Unrep	Unrep	200
[79]	2013	-	-	1	•				±29.4	±8.7	150 × 90 Unrep	Unrep	50
[80]	2013	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	200
[81]	2013	1	1	-	•				Unrep	±1500	Unrep Unrep	Unrep	100
[82]	2013	1	2	4	•				±58.9	N/A	69 × 28 × 07 15	1.59 × 10−5	100
[83]	2013	8	9	-	•				±78.5	±26.2	53 × 33 × 10 20	1.75 × 10−5	100
[84]	2013	-	53	-	•				Unrep	N/A	29 × 37 × 11 34	1.18 × 10−5	32

[85]	2014	-	-	3	•	•	•		±19.6	N/A	5 × 58 × 25 Unrep	7.25 × 10−6	Unrep
[86]	2014	-	21	-	•	•		•	Unrep	N/A	Unrep Unrep	Unrep	100
[87]	2014		9	9	•				±107.9	±15.7	50 × 40 × 16 36	3.20 × 10−5	500
[88]	2014	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[89]	2014	-	2	-	•	•	•	•	±19.6	±4.4	16 × 12 × 10 Unrep	1.92 × 10−6	100
[90]	2014	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[91]	2014	-	-	-	•	•	•	•	Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[92]	2014	-	-	60	•				Unrep	N/A	Unrep Unrep	Unrep	Unrep
[93]	2014	-	45	-	•	•	•	•	±19.6	N/A	Unrep Unrep	Unrep	32
[94]	2014	-	1	-				•	±9.8	±8.7	53 × 32 × 19 Unrep	3.22 × 10−5	Unrep
[95]	2014	-	1	1		•			Unrep	Unrep	Unrep Unrep	Unrep	Unrep
[96]	2014	10	-	-	•	•	•	•	Unrep	N/A	30 × 30 33	Unrep	100
[97]	2015	-	8	7		•			±107.9	±15.7	50 × 40 × 16 36	3.2 × 10−5	500
[98]	2015	-	-	3	•				Unrep	Unrep	Unrep	Unrep	50

Table E.2: Table adapted from [1], includes an overview of information from papers about inertial measurement units used in swimming. In the Swim Phase column, F stands for the free swimming phase, S stands for the Start phase and T stands for the turn phase.

Ref.	Filter Design	Data Storage (MB)	Data Trans.	Output Variables	Swim Phase F	Swim Phase S	Swim Phase T	Validation Methods
[15]	LP BW	Unrep	Unrep	stroke phase acceleration patterns	•			Video
[16]	Unrep	128	Unrep	stroke phase acceleration & angular velocity patterns, effect of fatigue	•			Video
[17]	LP BW	32	Unrep	stroke phase acceleration patterns, effect of fatigue	•			Video
[12]	LP BW (10 Hz)	Unrep	Unrep	stroke phase acceleration patterns	•			Video
[18]	LP HW (0.5 Hz)	Unrep	IR	stroke id, lap time, stroke count	•			Video & observation
[19]	Unrep	Unrep	Unrep	Stroke id, stroke count	•			Video & observation
[20]	Unrep	128	Unrep	stroke phase acceleration patterns	•			Video
[21]	LP HW (0.5 Hz)	Unrep	IR	Lap time, stroke count, stroke rate	•			Video & manual
[22]	LP BW	Unrep	Unrep	stroke phase patterns, arm joint angles	•			Video
[23]	LP (5 Hz)	Unrep	Unrep	lap count, lap time, stroke count, swim speed, distance	•			Unrep
[24]	Unrep	Unrep	Unrep	Hip rotation	•			Unrep
[25]	LP BW (0.01 Hz)	1000 Flash	Unrep	Velocity, distance per stroke	•			Manual
[26]	LP BW (10 Hz)	128 Flash	USB	stroke count, stroke rate, temporal stroke phase analysis	•			Video

[11]	LP HW (0.5 Hz)	Unrep	IR	stroke id, lap time, stroke count, stroke rate	•			Video & manual
[27]	LP HW (0.5 Hz)	128 Flash	RF, USB	acceleration, velocity	•			Tethered speed meter
[28]	LP BW (2.5 Hz)	Unrep	2.4 GHz RF	velocity, stroke rate, distance per stroke, intra stroke velocity	•			Unrep
[29]	Unrep	Unrep	Unrep	Acceleration profile recognition	•			Video
[30]	Unrep	1000 Flash	Unrep	Acceleration	•			Unrep
[31]	LP BW (0.01 Hz)	1000 Flash MMC	USB	velocity, lap time, time per stroke, stroke length, orientation	•			Video & observation
[32]	Unrep	Unrep	Wi-Fi, Bluetooth,	stroke id, average speed, pace, distance, stroke count, swim distance, lap count	•			Unrep
[33]	LP BW (0.5 Hz)	256	USB	kick rate, kick count	•			Video
[34]	LP BW (0.5 Hz)	256	USB	kick rate, kick count	•			Stopwatch
[35]	Unrep	Unrep	2.4 GHz RF	Arm acceleration and timing profiles	•			Video
[36]	Unrep	Unrep	Bluetooth, ZigBee	lap counter, lap time, stroke count, stroke length	•			Unrep
[37]	Unrep	Unrep	Unrep	lap count, stroke count	•			Unrep
[38]	LP (1 Hz)	Unrep	USB	stroke id, stroke count, stroke rate, stroke length, lap time, speed, force	•			Unrep
[39]	Unrep	Unrep	Unrep	stroke count, lap count	•			Unrep
[40]	LP BW (5 Hz)	4	RF	stroke count, stroke rate, lap count	•			Video
[41]	LP BW (5 Hz)	4	RF	stroke count, stroke rate, lap count, start and turn phase analysis	•	•	•	Video

[42]	LP	Unrep	Unrep	body orientation, speed, lap time	•		Unrep
[43]	Unrep	Unrep	Wireless	stroke phase acceleration and angular velocity profiles	•		Unrep
[44]	LP (5 Hz)	2	2.4 GHz RF	pitch and roll angles, breathing patterns	•		Unrep
[45]	LP BW (5 Hz)	4	RF	acceleration profile during turns		•	Video
[46]	Unrep	Unrep	Unrep	stroke id	•		Video
[47]	Unrep	Unrep	Unrep	angular velocity, temporal phase assessment, stroke rate, r index	•	•	Video & stopwatch
[48]	Unrep	Unrep	Unrep	speed, swim distance	•		Manual
[49]	Unrep	Unrep	RF	stroke id, lap time, stroke count	•		Unrep
[50]	LP BW (0.6 Hz)	512 Flash	USB	acceleration, angular velocity, pitch angle	•		Video
[51]	LP BW (0.5 Hz)	256	USB	kick rate	•		Video
[52]	Unrep	Unrep	RF	stroke phases	•		Unrep
[53]	LP HW (0.5 Hz)	1000	2.4 GHz RF	temporal stroke phase analysis	•		Video
[54]	Unrep	Unrep	2.4 GHz RF	Unrep	•		Unrep
[55]	Unrep	Unrep	Unrep	simulated arm stroke patterns	•		Video
[56]	LP HW (0.5 Hz)	1000	2.4 GHz RF	turn phase acceleration patterns		•	Video
[57]	LP BW (5 Hz)	4	RF	stroke count, stroke rate, stroke duration, lap count	•		Video

[58]	Unrep	Unrep	Unrep	stroke id	•			Unrep
[59]	MA	Unrep	Unrep	stroke id, stroke count, swimming intensity	•			Unrep
[60]	Unrep	Unrep	2.4 GHz RF	stroke id	•			Unrep
[61]	LP HW (0.5 Hz)	1000	2.4 GHz RF	mean velocity	•			Tethered speed meter
[62]	LP BW (0.01 Hz)	1000 Flash MMC	USB	velocity, lap time, time per stroke, stroke length, orientation	•			Video & observation
[63]	LP BW (0.5 Hz)	256	USB	kick rate, kick count, breathing patterns	•			Video
[64]	Unrep	Unrep	Unrep	instantaneous velocity, mean velocity	•			Tethered speed meter
[65]	Unrep	Unrep	Unrep	lap count, swim distance	•			Unrep
[66]	Unrep	Unrep	Unrep	stroke rate	•			Unrep
[67]	LP 0.5–5.0 Hz	Unrep	Unrep	stroke id	•			Unrep
[68]	LP BW (1 Hz)	4	RF	start and turn phase acceleration patterns, stroke count, stroke duration	•	•	•	Video
[69]	LP BW (1 Hz)	4	RF	turn phase acceleration patterns, temporal analysis			•	Video
[70]	HW FIR (0.5 Hz)	1000	2.4 GHz RF	arm symmetry, stroke rate	•			Video
[71]	LP BW (1 Hz)	4	RF	stroke count, stroke rate, lap count	•			Video
[72]	LP (100Hz)	Unrep	microSD	mean velocity	•			Tethered speed meter
[73]	LP (100Hz)	Unrep	microSD	energy expenditure, velocity, cycle velocity variation	•			Indirect calorimetry, lactate

[74]	Unrep	Unrep	Unrep	stroke phase acceleration patterns	•			Video
[75]	Unrep	2	RF	stroke rate	•			Unrep
[76]	Unrep	2	2.4 GHz RF	stroke count, stroke length, stroke rate, velocity	•			Unrep
[77]	Unrep	2	2.4 GHz RF	stroke rate	•			Unrep
[78]	MA	Unrep	SD	stroke id	•			Video
[79]	LP BW (5 Hz)	4	RF	block time, entry time, kick initiation time, stroke initiation time, kick rate, stroke rate, stroke count		•		Video
[80]	Unrep	Unrep	Bluetooth	stroke id	•			Unrep
[81]	LP BW (2 Hz)	Unrep	Unrep	body roll velocity	•			Video
[82]	HW FIR (0.5 Hz)	Unrep	Unrep	push-off velocity			•	Tethered speed meter
[83]	LP HW (0.5 Hz)	1000	2.4 GHz RF	mean velocity, stroke rate	•			Tethered speed meter
[84]	Unrep	Unrep	Unrep	speed, distance	•			Stopwatch
[85]	Unrep	Unrep	Bluetooth	stroke count, kick count, symmetry	•			Unrep
[86]	Unrep	Unrep	2.4 GHz RF	stroke count, mean velocity	•			Video
[87]	LP (100 Hz)	Unrep	microSD	energy expenditure, velocity, kick rate	•			Indirect calorimetry,
[88]	Unrep	Unrep	Unrep	stroke count, stroke id, lap count, lap time	•			Unrep
[89]	MA	NOR flash memory 64	433 MHz RF	stroke id, breathing patterns	•			Unrep

[90]	Unrep	Unrep	2.4 GHz RF	lap count	•	Unrep
[91]	Unrep	Unrep	Unrep	swim distance, lap count, lap time, stroke id	•	Unrep
[92]	Unrep	Unrep	Unrep	energy expenditure	•	Cosmed
[93]	Unrep	Unrep	Unrep	stroke id	•	Video
[94]	Unrep	Unrep	Bluetooth	joint angles during fly kick	•	Video
[95]	LP Fourier (8 Hz)	Unrep	Unrep	joint angles	•	Video
[96]	LP (2 Hz)	Unrep	Unrep	stroke id	•	Manual
[97]	LP (100Hz)	Unrep	microSD	mean velocity	•	Tethered speed meter
[98]	Unrep	Unrep	Unrep	Positioning	•	Video

F BODY BALANCE AWARENESS SURVEY

During swimming:

I actively adjust my body balance often

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

I notice when my body balance is flawed

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

I tend to forget my body posture

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

I am actively aware of the angle of my body

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

G INTERVIEW MINUTES VIBRATION METAPHOR EXPLORATION

Green mode: frequency and vibration length modulation.
Yellow mode: Intensity modulation.
Blue mode: binary on or off depending on threshold.

Participant 1

P puts on haptic motors on left and right side of side. Wearable in Green mode. P swims couple laps of freestyle.

R: Anything of note so far?

P: Yeah, I have the feeling that I feel vibrations more on one side than on the other. I don't know it is because I placed the motors differently. When I turn on one side I feel it more than on the other side. You're right, when in general when I swim the vibrations are actually very light. When I started to swim, I was like: 'oh I don't feel much'. So, then I need to be focussed on them and once you focus you can feel the vibrations.

At this point probably on of the motors was not working.

R: So how easy or difficult would you say is it to feel the vibrations?

P: On a scale of 1 to 10 from 10 is feeling it a lot and 1 not at all I would say about a 5 actually.

R: Did the vibration give you an indication on what to do?

P: Well, the point is you need to turn yourself when you breath for example. When I don't breathe it's really good for me cause I don't feel any vibration so it really works when I'm flat. But during freestyle you turn like every 3 times so then it's like too much because I need to turn all the time. Even when I don't breathe, I'm still moving my shoulders and hips. So In the end the vibration is not so useful or maybe not for freestyle because you're turning quite a lot. When I try to swim precise, I turn a lot with my hips and shoulders, maybe that's wrong.

R: It only should give you feedback when turning like this (showing with the hands turning on the median plane).

P: Really? Because every time I move I feel the vibration.

R: I have a filter that I can turn on. Could you turn around so I can enable that?

This is where it was found that the wearable was not working anymore. P tried to swim a few laps and do the calibration sequence again but there were no vibrations anymore. The user test was terminated here and continued another day.

P puts on haptic motors on the hips under the swimsuit. Wearable in Yellow mode. P swims couple laps of freestyle but also sometimes swims a little breaststroke.

R: So what did you notice?

P: When I do freestyle, I don't feel the vibrations. So I guess that means I'm swimming straight. But when I decided to swim breaststroke then I can feel it because my body is not properly flat. And yet, I think it's much better to put the sensor under your suit because you feel the vibration much better. But it depends if it might disturb some people. For me it's fine, but maybe some think it's too strong, but I'd rather feel the vibration.

R: Well, this is mainly about you. I'm going to ask other people and if they say it's uncomfortable I'll do something with that. So freestyle you don't feel any vibrations and breast stroke you do?

P: yes.

R: That could also be a calibration thing. Do you feel a difference between harder and softer vibrations?
P: No, I didn't know there were any differences.
R: Okay, let me see…
Checking the mode that the wearable is in right now. It seems to be in the yellow mode.
R: It should be that if you are past the threshold point it begins to ramp up. Did you notice any of that?
P: No, I didn't notice much. I can try again and be like more focussed on it.
R: Yeah, maybe you can try to sway a bit and see if you can feel it when you do freestyle as well. And just try to lean into it. See whether you can feel a difference.
P swims a couple of extra laps.
P: I hardly feel the intensity of the vibrations. Because usually what happens is, I'm flat, I don't feel it, then I start to lean a bit, then I start feeling the vibrations. And then when I'm fully straight I don't feel the vibrations anymore because I think that's the way it's set up. I feel it and then I don't. So I don't feel the difference.
R: you don't feel the difference, that's strange.
P: I think that it's really hard because it goes really fast. You go straight, and then you're not anymore.
R: could you place the vibrations a little bit higher
P: yeah, it moves around a little under my swimsuit so maybe it's better to use a sticker to hold it in place.
P places the vibration motors on het ribs under the elastic band. And swims a few laps.
R: Does it work?
P: Yeah it does work, but the thing is, when I put it under the stripe it's a bit uncomfortable. But other then that I can feel the vibrations.
R: Would you say you can feel the vibrations better than…
P: yeah! That's interesting because last time I put it under my swimsuit. And you would think that you feel more vibrations but this time both were equal even though this one is above. So I think this location is better than hips.
R: It could be the extra pressure from the elastic band holding it against your body.
P: yeah, that is probably what it is. Only thing is under the band feels uncomfortable.
R: So, you did feel the vibrations, not with freestyle still?
P: No, no, with freestyle and also breaststroke. I feel it with freestyle when I'm not fully flat but I didn't feel it when I was fully flat.
R: So if you vairy how flat you lay you do feel it?
P: yes.
R: good. You don't feel the softer vibrations?
P: uhm, No.
R: It's just very binary for you.
P: Yeah, for me it feels binary.
R: Alright, and does the feedback give you an indication on how you need to move?
P: Well, for freestyle there is not a big difference. When I do swim on different sides I won't feel any vibrations. So maybe at some point I'm not fully straight, but I don't feel the vibrations. I think when there is a variation I feel a big difference. (…)
R: Do you think that location is important for indicating how you should move?
P: You mean the location of the sensor?
R: Well, yeah, of the actuators.
P: I think it's more that at some places you feel it more. Like I felt it a little more on the ribs than on the hips. Maybe that's because of extra pressure. I think besides that it's just a matter of comfort.
R: So comfort and whether you can feel it are the most important thing

P: hm-hm.
R: Let's try the real binary mode.
R changes the vibration mode to the blue mode. P swims a couple laps of freestyle.
P: Okay, when I do freestyle I feel the vibration way more, like, way often. I always said I was completely flat but maybe I wasn't completely flat. It feels sometimes like the device is doing weird stuff because I think I lay really flat but I do still get vibrations. It could be me or the device. This mode just feels more sensitive. It might help me better for freestyle.
R: Would you say it's easier or more difficult to feel the vibrations?
P: It's the same but I felt it more often.
P places the actuators on the back and does a couple of lanes of freestyle.
P: I think there is not a big difference. But I think I feel it a little bit worse.
R: Let's also try to use the green mode (Explanation of the green mode)
R put device in the green mode. Swims a couple of laps freestyle.
P: This mode is really strange. I do feel the vibrations, no worries about that. But I don't feel it's accurate enough. When I tried different things, sometimes I felt the vibrations and sometimes I did not. It felt more random.
R: Did you understand what happens with the vibrations?
P: Sometimes I would swim really not straight and not feel vibrations. And then I would swim straight again and feel the vibrations. So for me it was confusing.
R: let's get back to the blue mode, you preferred that I believe? And we will do some backstroke.
P: yeah I think so.
R puts the wearable on the blue mode. The calibration was repeated only now on the back. P swam a couple of laps.
P: I felt the vibrations a bit to often. I felt the vibrations when I was in straight and when I was somewhat straight I didn't feel the vibration. When I started to use my arms, then during backstroke I felt like the feedback was not accurate enough. I really tried to swim as straight as possible but I still felt the vibrations maybe a bit too much
R: maybe the yellow mode is better for this one.
P: I was thinking the same.
R changes the mode to yellow. P swims a couple of laps.
P: Oh wow. This one is my favourite. Perfect. I was lying on my back, all good, I was straight and when I tried to put my ass a bit down in the water then I felt the vibrations and when I went straight, no nothing. This one is the most accurate, at least for the back stroke. And not confusing, not weird or 'oh, I don't know if this is real' it's the device.
R explains that we now go into recording mode and that we will record 300 meters of freestyle and 300 meters of backstroke. R puts wearable in recording mode. P swims the 600m. R concludes with a couple of final interview questions.
R: Can you describe which method of feedback you liked or didn't
P: There was one mode that was very confusing to me. I believe it was the Yellow mode, something with the threshold. I think for the freestyle my favourite was the blue mode because it was clear, I could feel the vibrations. So I don't have to focus too much whether the vibrations were still there.
When I did backstroke my favourite one was actually the yellow mode. I really liked it when I did backstroke. I didn't like the blue mode that much for backstroke. I tried the green one only for freestyle but I preferred the blue one I believe. The green one was confusing.
R: Is there a difference of importance between the two modalities? Or are they the same? For instance, do you feel like the feedback pattern is as important as the feedback location?
P: I think the feedback patterns are more important than the feedback location, because the location, even though I felt it a bit better on the front of my ribs than on my back, there is really a small difference. So I think feedback patterns are way more important than location.

R: Did you feel like the vibrations were in line with your swimming performance? Did you receive vibrations when you needed to receive vibrations?
P: It depends on the mode. But for the modes I told you about, so yellow for backstroke and blue for freestyle, then those ones were actually good. So yeah, it does help me.
R: Do you feel that with this wearable you could become a better swimmer?
P: Well, to be honest, of that I'm not sure because I think I need a little bit more technique and being flatter, I don't know if that would help me so much here. I think I would need more training o technique, on arms or legs but not really on like how straight I am.
R: Do you think it could help other people?
P: I think it might help some people who really start with swimming. Because you might not be able to fully lay flat. But for people who are used to swimming, I don't know if it's so useful.

Participant 2

R puts the vibration motors on the back in the loop where the band connects to the wearable. P starts calibration sequence by laying on its belly in the water. R sets the vibration mode into blue mode and P swims a couple of lanes.

R: Did you feel the vibrations?

P: yes, but not very clear.

R: Do you need more swimming to evaluate?

P: Well, the thing is I don't know when it does or doesn't vibrate. Because it vibrates when I do this. *(probably signing with hand about a roll motion)*

R: Do you want to try with an extra filter?

P: I'm not sure, it could be that I'm not laying the water correctly, it's hard to lay still while assuming your position.

R: Could you try getting it to vibrate while laying and not swimming.

P: Sure.

P laying in the water and changing its angle while not swimming.

P: It's vibrating.

R: so you do have control over that?

P: yeah.

R: So how well do you feel the vibrations

P: Not very well. Let me say it like this, you can feel it because you are focused on it but it might have disappeared (while swimming).

R: If I move the vibrator between the band?

R proceeds placing the vibration motor between the band and the skin of P. P proceeds to swim a couple of lanes.

P: This feel better but only one of them.

R: yeah, that could be right. On of the motors does not work well. If we do another calibration sequence it might fix it. But let's continue with just the one for now. Maybe do a couple more lanes and see if it helps with your position.

P proceeds doing a few laps of freestyle.

P: it didn't stop vibrating. It could be that my position was just not as good as I would think.

R: well, you just did the calibration. It could be that you lain a bit too high so the threshold is not right. But we could also move to a different vibration pattern.

R continues to explain the yellow mode, moves the vibration motors to the front and puts the vibration motors on the green mode. P continues to try the mode while laying in the water. Ans swims a few laps. R notices from the way P describes the mode that it made a mistake and continues putting it in the yellow mode. P swims a couple of laps with the yellow mode one.

P: The small vibrations are barely noticeable.

R: alright.

P: I'm going to try placing the motor on my breastplate.

R: Sure, go ahead, try that.

P puts the vibration motor on its breastplate and swims a couple of laps.

P: still, more noticeable on than on my back, but small vibrations are almost not noticeable.

R: Alright we can try a different location, I'm going to get some stickers for that.

While R is getting stickers, P places the vibration motor behind the head using the elastics of its goggles and continues laying in the water to try it.

P: This works surprisingly well.

R: What does? Oh, you put the motors on the back of your head.

P: Because then you also hear the vibrations.

R: Alright, maybe try a couple of laps like that then.

P does a couple of laps in yellow mode while the motor is behind the strap of its goggles.

P: Yes, this is by far the best.

R: do you have the feeling it gives an indication on how you need to lay in the water?
P uhm. It clearly show that I over calibrated it. So that I eight was to flat or to much leaned forward during the calibration.
R: would you like to calibrate again?
P: yes.
R puts wearable in calibration mode. P continues the calibration sequence. P swims a couple laps.
P: It does work. I don't know if I am assuming the right position, but I do notice that when I turn more forward it vibrates less. The only thing is, if it vibrates too much, I might get a bit of a headage. Maybe the neck would be better.
R: Do you think the location is important on how intuitive the feedback is?
P: The most important point is that you need to be able to feel the difference in vibration, because then you know if you're closer or not and that is not possible if it's on your body.
R explains green mode to P and turns the green mode. P goes on to swim a couple more lanes.
P: It was completely unintuitive. It just felt like random pulses.
R: alright, good to know. Let's do some backstroke.
R puts wearable in calibration mode. After P has calibrated the wearable is set to yellow mode and P does a couple laps and a test laying in the water.
P: Alright, conclusion, it is difficult to calibrate it well. On the other hand, maybe my position is not high enough.
R: I believe that your position is fine.
P: I over calibrate a little too easily.
R: we can try another calibration round.
P: also, the motor fell out of my goggles.
R: we can also try to put it in your neck.
P: Sure.
R and P do another calibration round. And the motor is placed in P's neck.
P: It works, if your ears are laying in the water, because they are so close you can hear what the motors are doing. Much better.
R: So you rather hear the motors than feel them.
P: Yes, because you can more easily hear the difference. I can try to add some extra sound (refers to swimming headphones) and is that works it's a win for me.
P proceeds by putting on its headphones and swimming a couple laps.
P: okay, it works, but on the head is better. And maybe a tip, there is not really a grace period.
R: What do you mean?
P: by the way this is just not a great spot (for placing the actuators). As soon as I feel vibrations I try to improve (my position). However, swimming is a bit too dynamic to do that well, you tend to be more busy with that than the swimming an sich. Maybe it's better to build a dead zone in the system.
R: Oh, so you are saying that the calibration should have an offset.
P: Small offset yes. For beginners that would be better. You will never lay perfectly, or at least you are busy too much with your body to always lay very straight in the water.
R: Alright let's go on for now. Can you describe which method of feedback you liked or didn't?
P: I did not like the one with pulses, I like the one with differences in vibration.
R: Is it more important to have the feedback on the right place on the body or that it has the right pattern.
P: Well, the thing is if you don't place it on the right spot on the body you won't notice the difference in pattern. I did notice that, especially with freestyle, because I'm a bit more familiar with that stroke, you can influence the vibrations and you can use it for training, absolutely.
R: did you receive vibrations when you needed vibrations?
P: I don't know if I needed them. But theoretically, if I wanted that line, then it does work.

R: Do you feel like the wearable could help you become a better swimmer?
P: Yes, the question is, am I on the right line or not. It does give a good indication on if you are on one line or not.
R: This is a bonus question. We have this hardware, would you like to receive feedback on something else, instead of only your swimming position.
P: Uhm, yeah.. Something that I’m a bit insecure about it how I need to move my legs.

Participant 3

R put the wearable in blue mode and placing the actuators on the back of P. P started calibrating the wearable. Had a little bit of trouble. seems that its back was less straight than previous participants. P swims couple of laps.

R: did you feel anything? what do you notice?

P: The wearable seems to shift during the turn. And the actuator fell out.

P proceeds to swim another few laps.

P: It's vibrating the whole time. But I don't know if I can lay any further forward.

R: So it could be that the calibration is not correct. I saw you hanging more forward than you might do during swimming.

R: How easy or difficult was it to feel the vibration?

P: Pretty difficult. The water interfered.

R: shall we repeat the calibration?

P: yeah, all right.

R puts wearable in calibration mode, P lays in the water. The calibration doesn't seem to catch.

P: Does it work?

R: it didn't catch, it could be that your back has a bit of a different shape than I'm used to from others and that I made the threshold for starting the calibration not sensitive enough. You can try putting the wearable lower on the back, see of that works.

P puts the wearable a bit lower on the back. and proceeds redoing the calibration. After a bit of struggle we managed to finish the calibration. Actuator is put on the front on the ribs.

P: I still feel very little.

R: Maybe it helps to put the wearable a bit tighter.

R helps putting on the wearable a bit tighter. R puts the mode to yellow. P swims a couple laps.

P: This feels very similar to blue. It also vibrated after the turn.

R: alright shall we also see how you experience this mode on the back.

R helps to put the actuator on the back. P swims a couple laps.

P: This already went better. I think that the back is better for me, but maybe a bit more directional. But I would rather do back than belly.

R: did you have the feeling the vibrations gave any feedback on what you needed to do?

P: It didn't feel gradual. The slope is just too small to really notice.

R puts the mode on the green mode. P swims a couple of laps.

P: It's not clear enough. Because the haptics don't make great contact, you don't really notice that it pulses.

R: so pulses are unclear, and that is because?

P: It doesn't always makes the best contact on the skin, you know, it moves sometimes, it makes the mode unclear. I think it's already good enough to get feedback as soon as you are not swimming straight to correct yourself. I don't know how clear it is to notice how crooked you're swimming. Since you correct rather quickly those pulses are maybe to slow.

R changes the mode back to yellow and calibration mode. P calibrates and swims a few laps.

R: what do you notice.

P: about the same as with freestyle. If you're not straight you get feedback and you pay attention to your body balance.

R: Do you notice that it gives feedback on how you are laying in the water?

P: I do find it tracks pretty good. If I go off balance on purpose, I notice that it vibrates and if I think that I'm swimming well it doesn't.

R changes the mode to blue, P swims some laps.

R: Did you experience that differently?

P: Yes, it seems to be going off the whole time, also if I'm swimming fully straight. It was more annoying so to say. Unless I was actually not swimming straight.

R: Anything else?

P: Backstroke is very annoying with all these people..
R: Do you still want to try a different spot on the body?
P: Location is fine, I think the vibration pattern is more important.
R: I'm now going to do a somewhat more general structured interview. Can you describe which method of receiving feedback you liked or didn't?
P: Binary (blue) I like the most. The middle one (yellow or green) is kinda annoying. It goes when you are only a little out of line.
R: and the green mode?
P: it doesn't feel very different from the binary mode. (yellow or green)
R: Is there a difference in importance of the 2 modalities of receiving feedback or are they the same? For instance: do you feel like the feedback pattern is as important as the feedback location?
P: I think that the way you give feedback is more important than the location.
R: Why do you think that?
P: For me the feedback is mostly a reminder to swim straight and than the location doesn't really matter. If I feel it then I know, I'm not straight. It's only one thing you have to improve, if there are more modalities to get feedback on location might be more important.
R: Do you feel like the vibrations were in line with your swimming performance, do you feel like you received vibrations when you needed to receive vibrations?
P: Yes, that I think so, except for with the yellow mode (might actually mean green)
R: Do you feel this wearable could help you become a better swimmer?
P: For me I don't really think so, because I already swim quite straight.
R: Then a last bonus question. Is there something you want feedback on, is there anything you would like the wearable to have?
P: I tend to forget to swim with my legs during freestyle. If I can get a vibration that helps me remind to pay attention to that, it would be better for me I think. Because I mainly use my arms during freestyle.
R: Maybe something for backstroke?
P: Something against getting water in my mouth, I'm always swallowing water but I don't really know what the cause is for that.