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Master-Thesis

Exploration of Agile Smart Footwear

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Aufgabenstellung:

Currently, shoes are a passive tool, which do not respond to a user's context such as to provide optimal workout performance or to warn when dangerous situations are to occur. In future, intelligent footwear should be able to; 1) understand the user and its needs by sensing the user's activity and respond to the environment, 2) by adjusting its properties, such as changing the rigidity, profile, and cushioning of the mid-sole or other parts of the shoe. There are different technologies explored already, such as using a shoe-placed inertial measurement unit (IMU) or relying on a capacitive insole. Shoe-placed actuators are yet to be broadly explored. This thesis can go in two different directions. On the one hand it can explore the recognition capabilities of different terrains, posture, gait, etc. Hereby a machine learning approach should be driven by relying on the state-of-the-art techniques, including a neuronal network approach. On the other hand, the thesis could have a look at the actuation side; how to the dynamically adjust a sole or other part of the shoe. It could be investigated to apply novel technologies, such as shape-changing polymers or other techniques and technologies, such as pneumatic air pressure chambers. Exploring smart materials, such as shape memory alloys and solenoids for an energy efficient actuation could be interesting to look at. Either way, the thesis will have a strong focus on the implementation part following a Do-It-Yourself (DIY) approach building a small series of footwear prototypes. As usual, the thesis kicks-off with a thorough literature review, that will reveal possible directions worth for exploration. The thesis will deploy a series of footwear prototypes, which closes with a short user evaluation.

Prof. Dr. Matthies

Exploration of Agile Smart Footwear

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A thesis submitted in fulfillment of the requirement to the degree
Master of Science (M.Sc.)

2022

Declaration of Authorship

I, Student Marco GABRECHT, declare that this thesis titled, “Exploration of Agile Smart Footwear” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly conducted while in candidature for a degree at Technical University of Applied Sciences Lübeck.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"Imagination is more important than knowledge.
Knowledge is limited. Imagination encircles the world."

Albert Einstein

TECHNICAL UNIVERSITY OF APPLIED SCIENCES LÜBECK

Abstract

Department of Electrical Engineering and Computer Science

Master of Science (M.Sc.)

Exploration of Agile Smart Footwear

by Student Marco GABRECHT

Smart wear, such as smartwatches or glasses is common. However, smart footwear is not common. This paper showcases the process of making a smart shoe, that can detect and simulate different terrains. The prototype consist of an vibration inlay and a pneumatic valve system that can inflate and deflate the front and back while increasing and decreasing pressure. The prototype is validated in three evaluations, two of which are pilot studies to validate previous research. It is shown how to reproduce that vibration increases stance time. Moreover, it was confirmed that soft terrain has an increased fluctuation in sensor data. The final evaluation concerns the simulation of terrain using an additional VR device, an Oculus Quest. Twenty users confirmed the realism of five simulated terrains to be fairly good, scoring 6.17 on a 11-point (0-10) Likert scale. In future, we envision the prototype to also be used as an AR/VR input device or to prevent injuries, by training to walk on changing, or uneven, terrains.

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The authors hope that students and researchers can benefit from the document and that more smart footwear can be developed with these findings.

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LIST OF ABBREVIATIONS

IMU	**I**antInertial **M**easurement **U**nit)
PCB	**P**oly**c**hlorierte **B**iphenyle
HCI	**H**uman **C**omputer **I**nteraction
PPG	**P**hoto-**P**lethysmo **G**raph
BT	**B**lue**t**ooth
EU	**E**uropean **U**nion
PWM	**P**ulse **W**idth **M**odulation
I2C	**I**nter-**I**ntegrated **C**ircuit
SPI	**S**erial **P**eripheral **I**nterface
RTOS	**R**eal-**T**ime **O**perating **S**ystem
FIFO	**F**irst **I**n - **F**irst **O**ut
MOSFET	**M**etal–**O**xide–**S**emiconductor **F**ield-**E**ffect **T**ransistor
LiPo	**L**ithium-**P**olymer-**A**kkumulator
LDO	**L**ow **D**rop **O**ut
VCC	**V**oltage at the **C**ommon **C**ollector
CAD	**C**omputer **A**ided **D**esign
TPU	**T**hermo**p**lastic **P**olyurethane elastomers
WiFi	**Wi**reless **Fi**delity
VR	**V**irtual **R**eality
AR	**A**ugmented **r**eality
API	**A**pplication **P**rogramming **I**nterface
3D	**three**-**D**imensional
FDM	**F**used **D**eposition **M**odeling
BMS	**B**attery **M**anagement **S**ystem

1 INTRODUCTION

1.1 Motivation

FIGURE 1.1: A visualisation of a shoe, that can analyse the movement and give statistical feedback*New AI-enabled 'smart' shoes to boost your fitness regime* [58]

No matter what your mission is, have some notion in your head. Forget the model, whether it's government or nonprofit or profit. Ask yourself

> *the more important question: Is my mission improving the world? Are you sure about it? Seek to disconfirm that all the time. And if you can, change your mission.*
>
> – *Jeff Bezos* [43]

To improve the world, it is necessary to find problems in it and address them. Only if the problem is known, is it possible to find a solution. The problem in this thesis is the missing innovation in smart foot ware. Smart wear, like watches, is a fix part of many lives, but smart footwear is not common[55]. Because it is not as common, there are fewer commercial products[68][24], than for smart watches[73]. The main reason is probably, that the benefit of a smart watch is huge with a display in range and many possible interactions. A smart shoe is mainly a sensor. There are products with useful features like heating, GPS tracking or self-lacing[23], but they are rare to come by. In Figure 1.1 a smart shoe is shown, that can give audio feedback from an KI assistant. There are smart shoes for gaming, helping to emulate the feeling of running and tracking the wearer[21], but this is a niche. A new product has to tackle many problems at once, like preventing injuries while running, being compatibly for gaming and feeling cozy. In this paper an attempt to explore such a prototype was made. It simulates different terrain and undergrounds in VR. As stated previously, this feature should help preventing injuries, by training the user to walk on different undergrounds[13] , while simultaneously creating a cozy and soft wearing experience.

To achieve these goals, my research, and with this my questioning is mainly focused on:

Q1 Is it possible to build a smart shoe, with pneumatic actuation, within a normal form factor?

Q2 Is it possible to build a smart shoe, that can simulate different terrains?

1.2 Organization

To find the answer to the research questions, there are some steps necessary. First of all, the existing research state has to be collected. Therefore chapter 2 gives an overview over existing footwear and the used technology. With the knowledge from other researchers, prototypes will be built to answer the research questions Q1 and Q2. Chapter 3 explains the prototypes and the process behind building them. All prototypes will be combined to one final Prototype with the advantages of all three. In chapter 4, participants evaluate the prototype, by testing it in a short study. The prototype has to generate similar results, as the related papers[51][50][85] outlined in chapter 2. The research question Q2 have a new aspect and therefore the internal validity has to be proven, this will be done in chapter 4. Chapter 5 functions as a discussion and reiterates all contributions in detail, with key insights and portrays on how the findings can be applied in general. A comparison with other findings will be conducted as well. At the end some recommendations for future research will be given. The last chapter, chapter 6, will be the conclusion. In it, the contributions will be reiterated and outlined.

1.3 Methodology

The evaluation part of this paper have three different data collection types. All three are all predominantly qualitative and not quantitative, as they all have a limited number of participants. The secondary data will be generated from other papers and research in smart foot-ware and used to build an own prototype.
This prototype will be used to gather different data, via sensors. Over the course of different rounds of experiments, evaluating the current prototype, the prototype will be updated. The first two evaluations have experiments using measured sensor data from an IMU and two pressure chambers. The data will be analysed and compared to other findings and the last evaluation include a survey. This survey show if the prototype can simulate terrains in a way, the participants find realistically.

1.4 Contributions

The main contribution of this paper is an Artifact Contribution. The prototype that is built is documented and can be replicated. The second contribution is a Dataset Contribution, the data from the three evaluations can be used to validate other findings. The survey from the last evaluation is a Survey Contribution. The data can be used to analyse the effect of changes in shoe to the human reaction.

2 RELATED WORK

This chapter describes the research conducted regarding smart footwear and different attempts at creating it.

FIGURE 2.1: Different smart foot-ware prototypes
Vibration Prototype[53], Sensor insole[28], Center of pressure detection[30], terrain detection[50], tickle shoe[31], vision and vibration insole[29]

2.1 Smart footwear

The topic of smart footwear is not new and many papers exist focusing on and thus measuring different data. Often these measurements are used to detect human errors or illnesses. In some cases these prototypes provide additional input methods for the user to interact with. Only a small amount of papers are giving feedback to the users, by utilizing the sole, sending feedback directly to the foot. And out of these a very small amount is changing the sole properties, by using pressurised chambers or other real time means. The following pages

will provide an overview over some papers, that are relevant for the prototype that will be built. In Figure 2.1 some images of prototypes from these papers are shown.

2.2 Sensors

Sensors are used to generate measurements. With these measurements many hypotheses are proven. The range of available sensors is huge. Mentioned here are only sensors, that are used in footwear. The following are only some papers regarding sensors, there are many more.

2.2.1 Acceleration and Rotation

An IMU can measure movements and changes in this movement. With these values even small changes can be quantified. With the help of the gravity the rotation to ground, angular velocity, can be measured. This can be seen in Figure 2.2. This sensor is used in "mobiLLD: Exploring the Detection of Leg Length Discrepancy and altering Gait with Mobile Smart Insoles"[51] or many commercial products like Styrd.

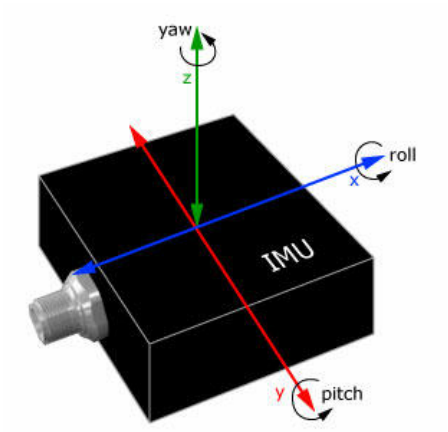

FIGURE 2.2: IMU: Internal Measurement Unit, that can measure six movement values

2.2.2 Pressure

The pressure in different regions of the shoe can visualize the ground contact, by showing an heat map, or center of pressure like discussed in ”GymSoles: Improving Squats and Dead-Lifs by Visualizing the User’s Center of Pressure”[30]. This sensor was also used to determine stress, through measuring how strong and often the ground contact is, in ”StressFoot: Uncovering the Potential of the Foot for Acute Stress Sensing in Sitting Posture”[28].

2.2.3 Heat and humidity

The paper ”Arduino Controlled Cooling Smart Footwear”[57], contains many different sensors like temperature and humidity sensors. Most humidity sensors have a temperature sensor combined to calibrate the sensor. This measurements can be used to analyse the needed ventilation of the footwear. A common humidity sensor (BMP180) can be seen in Figure 2.3.

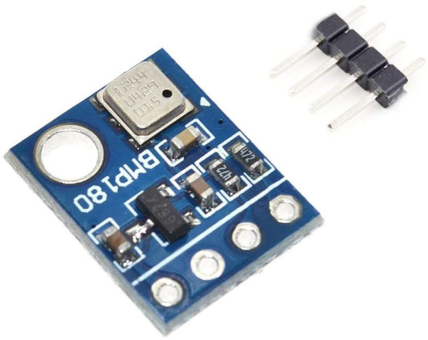

FIGURE 2.3: BMP180: Common Temperature and humidity sensor on an PCB

2.2.4 Deformation

Strain gauges can be used to recognize stretch, bend and pressure changing, in the Paper ”Wearable stretch sensors for human movement monitoring and fall

detection in ergonomics”[18], this is shown with some different types of sensors. These recognition’s are important for building a digital twin and compare stretches in different tasks.

2.2.5 Speed with air

The Stryd sensor system can calculate the foot speed through a heating element, by measuring the cooling of the surrounding air. The sensor values of Stryd are proven in the paper ”Validity of the Stryd Power Meter in Measuring Running Parameters at Submaximal Speeds”[40]. Speed measurements are essential to calculate physical forces.

2.2.6 GPS

The aforementioned paper ”Arduino Controlled Cooling Smart Footwear”[57], also contains usage of a different sensors, GPS. The GPS values can be used to track the user and load values from the internet or measure height differences, speed and distance.

2.2.7 Capacity

A terrain detection was created in this paper ”ShoeSoleSense: Proof of Concept for a Wearable Foot Interface for Virtual and Real Environments”([52], which used a self built capacity. Expanding on this approach, of using capacity plates for terrain detection, is ”CapWalk: A Capacitive Recognition of Walking-Based Activities as a Wearable Assistive Technology”[38] and this method was used to recognise different undergrounds in ”CapSoles: who is walking on what kind of floor?”[50]. The principal of an capacitor can be seen in Figure 2.4.

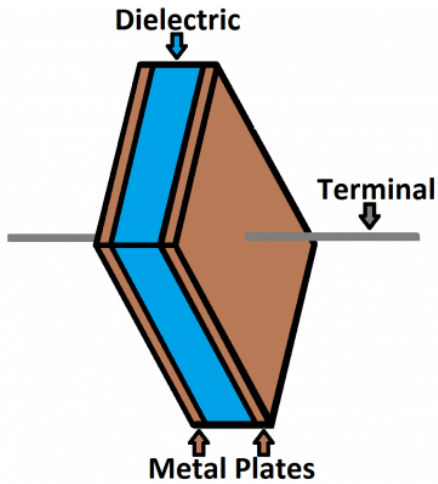

FIGURE 2.4: Structure of an Capacitor[15]

2.2.8 Light

Through the usage of infrared light, heat and different blood values can be measured[22][37]. One of these values is blood sugar. Green light can be used to measure different values, like the Photoplethysmograph (PPG) sensor, that can determine blood movement and therefore blood pressure and pulse[88].

2.2.9 Microphone

Microphones can detect lightweight signals, as shown in the Paper ”Estimation of temporal gait parameters using a wearable microphone-sensor-based system”[82] in which they successfully estimate the gait parameters using only a microphone system.

2.2.10 Camera

Camera systems can track the users posture and the angles of their joints, like presented in ”Cluster analysis to identify foot motion patterns in children with flexible flatfeet using gait analysis—A statistical approach to detect decompensated pathology?”[11] or ”Design of a bladder based elastomeric Smart Shoe for

haptic terrain display"[84]. The used system is integrated in a bigger system and can be seen in Figure 2.5. This is especially helpful to prevent injuries or misalignment of the ligaments.

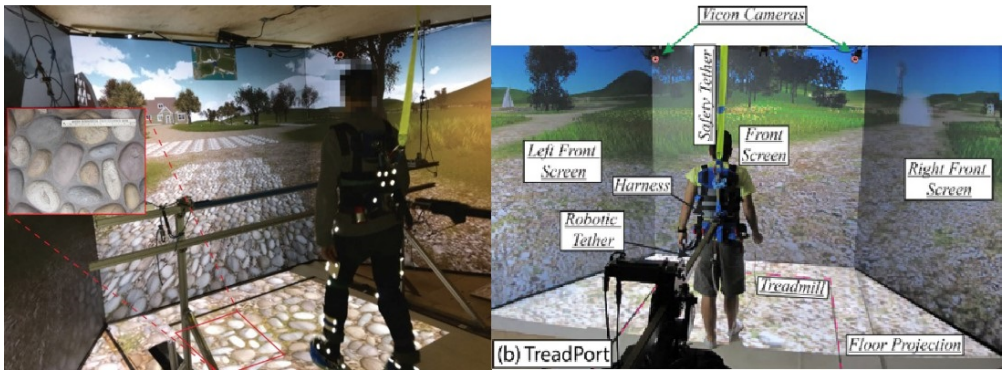

FIGURE 2.5: Camera tracking system with tracking markers on person to recognize the angle of the joints[84], this is in an VR-CAVE with an treadmill

2.3 Feedback/Actuators

There are different kinds of feedback like acoustic, visual and haptic feedback. The hearing sense is the fastest sense[86] followed by the haptic sense which is faster than the visual sense[27]. Because the shoe is not in a good range for utilizing these senses, smell and taste are not considered in this approach.

2.3.0.1 Vibration

Vibration is an important topic for smart tech, because the human reaction to it is fast and the vibrating sensation is easy to produce. For example in this study "VIBROTACTILE DISPLAYS FOR IMPROVING SPATIAL AWARENESS"[67] the reaction time using a visual system with vibration have a significant decrease in reaction time, over only visual system. In different approaches, like the paper "Application of tactile displays in sports: where to, how and when to move"[79] they agree on the fact, that vibration is an effective actuator, even if the results didn't show a increase in speed, by finding the correct position. In

shoes there are also vibration feedback prototypes, like in ”mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles”[51]. The prototype can be seen in Figure 2.6. More in subsection 2.4.1. This paper ”Exploring Vibrotactile Feedback on the Body and Foot for the Purpose of Pedestrian Navigation”[54], has a relevant part where measurements on the sensitivity of different body parts are conducted. This knowledge can be used to estimation where the vibration motors have to be placed and in what distance.

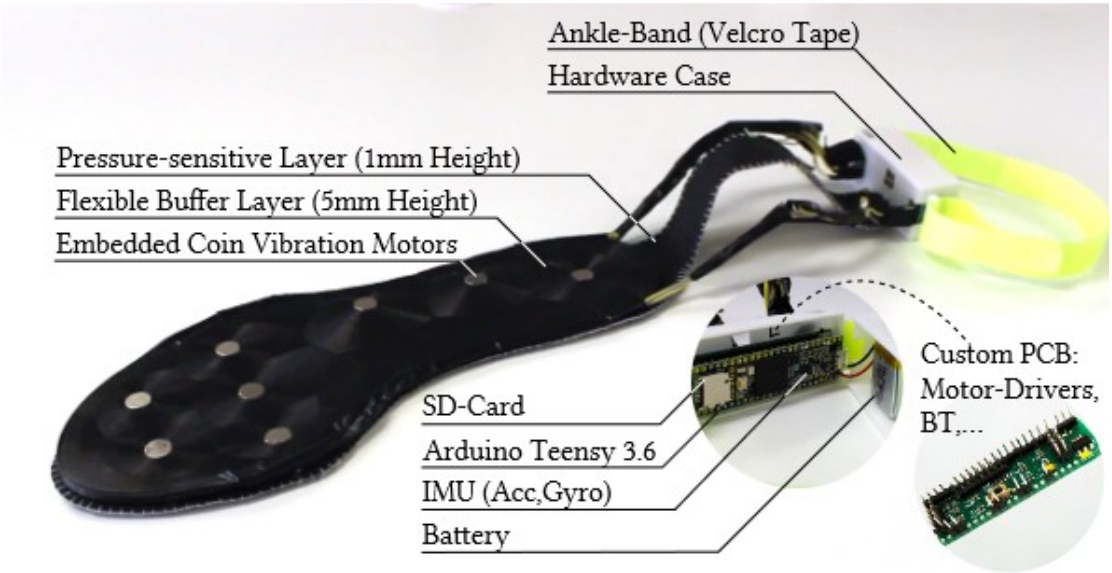

FIGURE 2.6: Prototype from ”MobiLL”[51] with vibration motors and sensors, with pressure sensitive layer in an insole.

2.3.0.2 Servomotor

Servomotors can move to a fixed position and therefore move against a human to generate a haptic feedback. The paper ”Auto-Moto Shoes: An Automated Walking Assistance for Arthritis Patients”[66],can compensate the underground height. This can be used to simulate almost flat underground an on non flat terrain or vise versa.

2.3.0.3 Solenoids

Solenoids, are electromagnetic actuators. They have two states and can move their inner core, this core can press against an object or move their mass to provide a shock. The most commonly used method in footwear is the valve, this is described in greater detail in section 2.3.0.6.

2.3.0.4 Other compression

There are several other actuators to compress something and squeeze as feedback. An interesting option is fabric, that can compress like in this paper ”Touch me Gently : Recreating the Perception of Touch using a Shape-Memory Alloy Matrix”[56]. This can be used to give an tight fit or squeeze feedback.

2.3.0.5 Auditive

Auditive Feedback is an effective warning system. In ”Embedding pressure sensor in a footwear for checking the weight distribution during standing”[35] a buzzer is used to warn the person, if the weight distribution on the sole is uneven. An actual product has an AI coach, that gives dynamic audio feedback, based on users' real-time performance and training[58].

2.3.0.6 Air Chambers

The use of air-chambers is well researched, an sphygmomanometer is basically an air chamber with a sensor. An interesting actuation system of this concept is described in this patent, it has an air-chamber system, with passive pressure generation and changing chambers [89]. There is a comparable paper to the goal of this thesis. It is named ”Design and Evaluation of a Soft Robotic Smart Shoe for Haptic Terrain Rendering”[84]. This prototype can simulate objects under the shoe, or different heights. The tests with this prototype showed, that the participants can recognise inflated chambers, however, it only mentioned a simulation of different terrains and didn't study it as part of the research. The

terrain simulation is performed in this paper ”Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study”[85]. The results are an increase of realism in simulating cobblestone.

2.3.1 Other foot ware actuators

In this paper ”TickleFoot: Design, Development and Evaluation of a Novel Foot-Tickling Mechanism That Can Evoke laughter”[31] an electric motor is used with a tip, to tickle the foot. This concept can be seen in Figure 2.7. Another interesting although slower feedback is heat, as discussed in ”ShoeSoleSense: Proof of Concept for a Wearable Foot Interface for Virtual and Real Environments”([52]

FIGURE 2.7: Prototype with tickle mechanism[31] consist of four layers and brushes, that can move, to tickle.

2.3.2 Visual Feedback

An interesting paper regarding footwear with a visual feedback is ”Gym-Soles++: Combining Google Glass with Smart Insoles to Improve Body Posture when Performing Squats”[29], here google glasses are used to display feedback for the measured posture, in a direct and visual way.

2.4 Similar prototypes

Because some of the prototypes are similar to the prototype, that will be built, they get explained in greater detail.

2.4.1 mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles[51]

This prototype can be seen in Figure 2.6. It has a pressure sensitive inlay with 16 pressure points, to measure the weight distribution and reconstruct the gait cycle. On top are 8 coin vibration motors in a flexible Buffer Layer (5mm height). The IMU, a micro controller, a custom pcb with motor controllers, Bluetooth® and a battery are fixed externally to the ancle using a fixture band. The study in this paper has shown that the stance time can be increased through vibration. Some of these design choices can be considered when building an own prototype, like the thickness of the flexible buffer to embed the coin vibration motors and some motor positions.

2.4.2 CapSoles: who is walking on what kind of floor[50]?

This prototype can be seen in Figure 2.8. It consist of capacitor plates that are connected to an Arduino nano with a Bluetooth® module. The electronics are stored in an box, attached to the ankle, only the 6 capacitive layers are embedded in the insole. The Bluetooth® module can stream the data directly to an external recipient. The findings are that soft undergrounds have unstable measurements and therefore can be considered as easily distinguishable. Overall the 6 undergrounds, sand, lawn, pavement, tartan, linoleum, carpet can be distinguished with an average certainty of 82.46%. But the main relevant finding for this thesis remains, that soft undergrounds can be easily distinguished, by analysing noise in the signal.

FIGURE 2.8: Prototype from CapSoles, with assembly steps[50]. The monitor shows sensor data and activation of vibration motors.

2.4.3 Conclusion of other prototypes

There are many different actuators and footwear. One of them is trying to simulate different undergrounds[85]. Another paper provides a simulation of different frictions "DEVELOPMENT OF A COMPUTATIONAL MODEL FOR SHOE-FLOOR-CONTAMINANT FRICTION"[10], but this is not really what this thesis will tackle. The papers regarding simulation of VR terrains from Yue Wang[85], showed that the terrain simulation is a promising topic, therefore this topic is worth to explore more. This thesis will focus more on performing the cushioning, damping and vibrations and not rendering obstacles.
The most prototypes have an external box or wire[50][30][66][31] and don't store micro-controllers directly in the shoe, because it is easier and more robust

of a prototype. The prototype from this thesis will completely fit in a shoe. This prototype will fill the research gap of smart foot ware in an normal form factor with an active changing in damping with pneumatic in a simulating way.

In summary, the main findings of related papers regarding this thesis are:

- The field of terrain simulation using smart footwear could use more research.
- Multiple presented prototypes can measure physical parameters using a multitude of sensors.
- Some prototypes can alter shoe properties by using actuators.
- A change in human behavior can be achieved by using actuation like vibration.

3 PROTOTYPES

This chapter contains an overview of the prototypes, that will be needed throughout the rest of the thesis. It walks through the building process of the prototypes from planning to production, and discusses the functionality and design decisions of each part. Sections 3.1 through 3.3.2 describe different iterations and development of specific components in greater detail.

3.1 Overview of the prototypes

Throughout this chapter three intermediate functional prototypes will be documented and constructed, that each focus on one functionality. These will later be combined to form the final prototype, while combining the functionalities. This prototype will alter the sole of a shoe and measure the impact of this change. The subsequent evaluation requires at least one dummy prototype and one functional prototype to compare measurements. Therefore it will examine the behavior while wearing a dummy, which consists of a sole with no active changes within the gait cycle, to a functional prototype. This prototype will actively change properties of the insole to explore the effect of changing properties while running. Functional prototype one, the air-pressure prototype, will integrate air-pressure-chambers and change the pressure in this chambers. The

final air pressure prototype can be seen in Figure 3.1 on the right side. Functional prototype two, the vibrating prototype, contains active vibration motors and will simulate a change in the insole with vibration, like other Papers[51] demonstrated. This prototype can be seen in Figure 3.1 on the left.

FIGURE 3.1: One Prototype Iteration, on the left is the Vibration inlay and on the right the sole with pressure chambers and PCB

3.2 Requirements

To qualify as a functioning prototype, the prototypes must meet a multitude of requirements. These requirements are categorized into the following topics:

- Global Requirements (R1-R6)
- Mechanical Requirements (R7-R17)
- Optional Requirements (R18-R22)

The global requirements are requirements that are equal for all prototypes and define the overall physical limits and dimensions. Mechanical requirements are different for each prototype. Optional requirements are nice to have, but not necessary for this thesis.

3.2.1 Global Requirements

All three prototypes need to comply with the global requirements, which are as followed:

R1 For ease of comparison the dimensions of the soles all need to be equal (EU 42).

R2 They all need the same sensors system with equal sensor positions.

R3 They all need a measuring period of 10ms.

R4 The data needs to be transmitted to a server with a maximum delay of 5 seconds.

R5 They all must withstand the force of a running person with a bodyweight of 90 kg on asphalt, which equates to about 2000N.

R6 They all need a working period of one hour or more.

3.2.2 Mechanical Requirements

The mechanical requirements for functional prototype one are:

R7 Prototype one needs an active valve system, which changes the damping and height of the sole noticeably.

R8 The prototype needs functional valves, that can let surrounding air in each of the two pressure chambers.

R9 The prototype needs functional valves, that can direct air from one chamber to the other.

R10 The chambers needs to be relatively airtight, so that they can hold pressure over normal level for more than 10 seconds.

R11 The valves need to close and open faster than the measuring interval (10ms).

R12 The valves and chambers have to withstand more than 2000N pressure.

The mechanical requirements for functional prototype two are:

R13 The vibration system has to vibrate noticeable.

R14 The vibration strength has to be adjustable.

R15 The prototype has to withstand continuous vibration for more than 10 minutes.

R16 The vibration motors have to be arranged in the front, middle and back.

R17 The vibration motors have to be controlled individually.

The dummy prototype doesn't need additional mechanical requirements.

3.2.3 Optional Requirements

There are optional requirements, these will help conducting the evaluation when they are met, but are not necessary. They will however increase the accuracy of the evaluation.

R18 Same weight - If the prototypes have the same weight the measured values are better comparable.

R19 Same medium damping - The standard damping and flexibility have to be the same to better compare the prototypes.

R20 Same weight distribution - The weight distribution may change the way of walking or measured impact.

R21 Same optic (blind study) - No one should differentiate the prototypes by sight. Therefore an influence can be excluded.

R22 All intermediate prototypes are combined in the same resulting body - This reduces bias in the evaluation participants.

3.3 Prototypes

As discussed earlier, the three main functionalities will be explored separately. They will be implemented in different intermediate prototypes. At the end, all concepts will be merged into one final prototype. This process produces many iterations of different prototypes with improvements and changes. Not every iteration will be documented in this thesis, but Figure 3.2 shows a few of the discarded iterations.

FIGURE 3.2: A few of the outdated prototypes and material tests.

3.3.1 Designing the shape

Creating an useful sole shape can take many different directions, but as the overall shape of commercial insoles are already well designed, they prove a good starting point. Using the 3D-scan of a commercial sole it can be recreated and used for the outer prototype shape. Because the functioning prototypes need a specific thickness the biggest available thickness of a sole is chosen. The air-pressure prototype spans the largest base volume and is thus used as gauge. The Design is created using Fusion 360, which is a CAD program and is free for educational use. This enables a large group of people to later view and edit the CAD files. All files are freely available for download[1]. The prototypes will be designed for foot-size 42EU, as the chosen participants for the small user study have been selected for this foot type, which is average in Germany [71]. Other ideas were to generate an optimised shape with Gensole [34], this tool can generate an orthopedic correct shape of an sole. These prototypes will be tested with different users and therefore an over customised shoe would not sued the needs of this study, therefore the first approach was chosen. The designed shape will be same for all prototypes, meeting R1.

3.3.2 Dummy prototype

As Baseline of the aforementioned study the dummy prototype will be used. This ensueres equal comparison for all functioning prototypes. This prototype has no active changing functionality and contains only the needed measuring system(R2). Therefore a 3D-printed insole with the same shape as the following prototypes will be produced.(R1) It will be 3D-printed, as it 3D-Printing is a well used technology in prototyping[63][6] and can provide the needed shape in an easy to use and accessible form. Another benefit of 3D-Printing is the repeatability among other researchers, if they so please. Furthermore changing of characteristics are fast implemented. In Figure 3.3 the first Dummy prototype can be seen. The straps are temporary and the micro-controller is stored in a yellow box on the left side, the sensors and battery are build into the sole.

[1] https://github.com/susesKaninchen/SimulatingShoe

FIGURE 3.3: Dummy prototype V1, with IMU, ESP32 mini and temporary attachment.

3.3.3 Vibration prototype

Vibrations within an insole can change a persons behaviour [51], but it can not change real terrain properties. This prototype is build to simulate terrain change. Vibration motors are fit inside the insole in different positions(R16). Different vibration strengths(R14) and motors(R17) will be activated to simulate changes to the terrain. An example of the first vibration prototype van be seen in figure 3.4. The Mounting mechanism have greatly evolved and the Micro controller with the IMU(R2) and the battery pack is build in the sole.

3.3.4 Air-pressure prototype

This prototype has two chambers within the sole, one in the back, where the heel of the foot rests, generating pressure while walking and running and one in the front, that can expand and change the properties within the given pressure.

FIGURE 3.4: Vibration prototype V1, embedded to an shoe with IMU, ESP32 mini and six vibration motors in an damping layer

The prototype will change the pressure while running and simulate different properties of the terrain. The heel chamber is smaller and therefore can produce more pressure, the front chamber is larger and need more air to build up the same pressure. One prototype iteration can be seen in figure 3.5. The chambers are split from the insole and the electronics are separated. The chambers can be changed with different stiffness and can have a support structure, to prevent or force warping in different places. One of these preventions can be seen in Figure 3.11. The lines in the chambers hold the top and bottom together. They are also needed to support the surface while printing[1].

3.4 Sensors

A critical part of all prototypes is the validation, which is done via sensor values. If the prototypes has an impact, than the sensor data has to change congenial to this impact. For the sensor data to be reliable and meaningful is thus of great

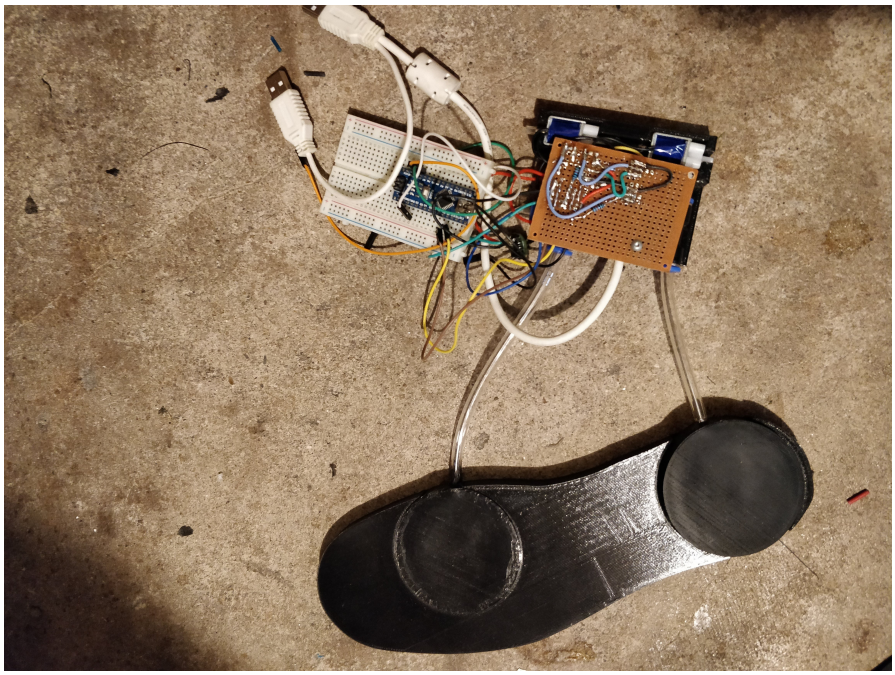

FIGURE 3.5: Air-pressure prototype V1 with two removable round chambers and external valve system and an Arduino nano connected to the pressure sensors

importance. To measure different forces there is one accelerometer, one gyroscope, and two pressure sensors for the pressure chambers. The IMU position is chosen, because it is explored in another paper and is possible to measure the ground reaction force[12]. The chamber system is rather new and the pressure sensors will replace other contact force sensors.

3.4.1 Building the sensor system

A stable sensor placement is essential, because of that, the sensors need a stable mounting system. The sensor will be in the center of the sole pressed in place. The accelerometer and gyroscope sensor (MPU6050) is on the main PCB and the pressure sensors connected through cables, because they have to measure the pressure directly at the chambers and the position can be seen in Figure 3.11.

3.4.2 Validate the Sensor System

To validate the sensor system the measured data will be tested against fixed actions. The pressure will be verified using three forces with known weight and known contact area. The measurements are expected to be linear, as the measured pressure depicts the surface pressure, which is linear[65]. The accelerometer and gyroscope will be slowly rotated in every direction and the earth gravitation has to display a constant measured force in one direction, as this is the strongest force impacting the sensor [59].
The prototypical sensor system passed all these tests.

3.5 Actuators

To change the damping and vibration, the two different mechanisms, vibrating and air-flow, are controlled via micro controller from a computer or roles implemented on the micro controller. The changing mechanism of the vibration prototype is comprised of 6 pressure points, as shown in Figure 3.6(R16), and different vibration strengths(R14), further explained in the next subsection 3.5.1. The air-pressure prototype contains pressure chambers, that inflate and deflate, changing the stiffness of themselves in different levels. The layout of these can be seen in figure 3.11, explained in more detail in section 3.5.2

3.5.1 Vibration mechanism

To create vibration in such an small space there are different ways. A Coin-cell vibration motor near the foot is possibly a good solution, as shown in the paper mobiLDD[51]. The coin-cell vibration motor is chosen for the prototypes, as it has proven to impact the human nerve receptors fast and reliable. To control them with different strengths a MOSFET with a PWM signal can be used(R14). It should be remembered, that the load is an inductive load and the coin-cell-motor generates electricity. To overcome this a by-pass-diode and a small capacitor buffer will be added. Six of the MOSFET stages will be in every sole(R17). Aside

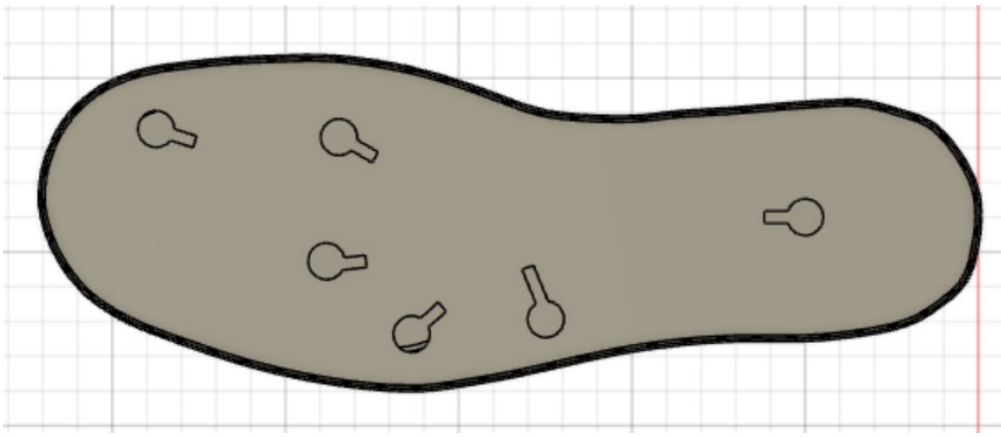

FIGURE 3.6: Layout of the Coin-cell vibration motors in Fusion360, with cable guide to fixate the motors

from indentations for cables and the motors no extra hardware modifications are necessary.

3.5.2 Inflate mechanism

The inflate mechanism needs a pressure generator and valves for pressure regulation. A commercial pressure generator is not suitable for the space. Furthermore a pressure generator induces vibrations and additional weight. Another solution is to use the mechanical energy produced while moving in the shoes. If one chamber will be used to generate the pressure, other chambers can be inflated using this pressure.
The pressure in all chambers must be monitored to enable control using software. To achieve the monitoring a very fast pressure sensor(R3) is needed in every chamber, as well as two valves. One valve connects the interior chambers(R7), the other enables air intake from and release to the environment(R8). The valves have to be strong, light, fast and small. In such a tiny space it is not common to have all of these parameters met. As only positive pressure will be built within the chambers, it is possible to use self closing valves. These can close by themselves in one direction, without the need for external energy. Because the valves have the highest power consumption (400ma each) and are closed most of the time, this reduces the power-consumption of the system drastically.
The only remaining problem is the connection between the two chambers(R9).

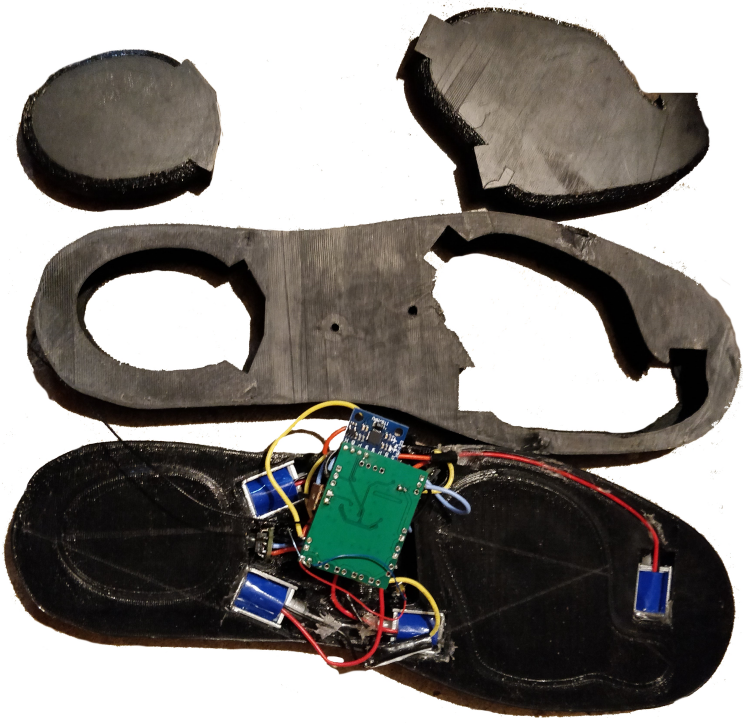

FIGURE 3.7: Air-pressure prototype V2(bottom) and V3(top), the step of splitting the sole in two single chambers and changing the materials from dasFilament TPU to ninjatek Chinchilla for the sole and ninjatek ninjaflex for the chambers

The pressure is too high to withstand forces from two different directions, because of this there are two valves oriented oppositely. The valves are inductive loads and will generate negative voltages when they release. To overcome these negative voltages and save the micro controller, the same system as by the vibration motors will be used. Additionally the motors are connected to the battery pack directly and not to the same 5V system as the micro controller. The final air chamber iteration can be seen in figure 3.7. The chambers are constructed as removable components for a prolonged lifetime and a better airtight seal(R10). The material of the sole part was switched to ”Chinchilla” from ninjatek.

3.6 Hardware decisions and implementation

The hardware is an essential part of the project. Every part of the hardware was specially chosen to be open source and easily replaceable, as the results may vary when replacing them.

3.6.1 Electronics

The electronic part consists of a micro controller, a gyroscope, an accelerometer, an air pressure sensors, a MOSFET stage, some coin-cell vibration motors and some valves. Every part has to be suitable for the present task of simulating terrains and affecting gait.

- **Micro controller**
  As micro controller an ESP32 with a small form factor and all needed passive components built in, is used. The ESP32-S2-MINI-1U-N4[77] is fast enough to manage the necessary readings(R3) in real-time, as well as coordinating all actions. It also has a WiFi option, to send and receive data(R4) and many pins to operate actuators and sensors.
  The FreeRTOS[78] on the ESP32 is a real time operating system that can handle context switches, gathering precise measurements and uploading data in the background. It features I2C and SPI[76] if more sensors need to be connected. While the analog readings are not precise[32], they are adequate for pressure readings, as only values are compared, both being measured equally imprecise. The antenna is external and can be positioned as needed for a better connection. Because of all these features this micro controller is often used in many applications[8][46][14].

- **Gyroscope and Accelerometer**
  The gyro and accelerometer sensor is the MPU6050[41]. This sensor was chosen, because of it's many use cases[7][81][70][75][44][45], which renders the results of this thesis comparable to other papers and findings. The MPU6000 has a SPI interface and is therefore faster, but it was harder to procure and the I2C interface in fast mode proved to be fast enough

(>0.800ms)(R3). If necessary, a magnetometer can be added and the readings can be faster with the FIFO-queue on the chip. The breakout board was used, because it is cheaper compared to a single chip and easy to solder.

- **Air pressure sensor**
  The air pressure sensor has to be fast in order to read the pressure and adjust it in time. The sensor has to withstand huge forces(R5), as the user will accelerate their whole body mass while running and the chambers will be hit with the complete force. The analog sensor XGZP6847A300KPGPN33 [17] is a sensor, that will withstand -100kpa to 300 kpa(R5) and map it to an analog voltage instantaneously(R3) also streaming it continuously. The version of this sensor is an 3.3Volt version, because the ESP32 is a 3.3V micro controller. Other sensors with the hx710b[69] chip would take more than 100 ms to read one value[26]. The XGZP6847 is used in some other smart wear, not related to footwear, for which papers show great measurement results[47][83][62].

- **MOSFET Stage**
  The MOSFET Stage has to continuously deliver power for one coin cell vibration motor or short duration pulsed for up to two valves. This prototype uses the SSM3K7002KFU,LF[74], which has a diminutive form factor and can deliver up to 400ma continuously and 1.2A pulsed(R10).
  Because they will power inductive loads there is need for a freewheeling diode parallel to the load cutting off the negative voltages generated by the inductive load. Additionally, there is an 680Ohm resistor and 10μF capacitor reducing the effect even more. This MOSFET Stage has a pull-down resistor with 100kOhm and a limiting resistor with 1kOhm to protect the pins of the ESP32 to reduce the current flow to under 40mA, which is the maximum current of the digital outputs of the ESP32, that can be delivered without destruction. In Figure 3.8 the effectiveness of this stage can bee seen. The voltage differs only by 200mV within a period of 11.2 nanoseconds. Because the sensor readings are performed every 10ms and the ripple occurs after them, these differences have no effect on them.

- **Coin-cell Vibration Motors**
  The vibration motors have to fit into the sole and vibrate strong enough to

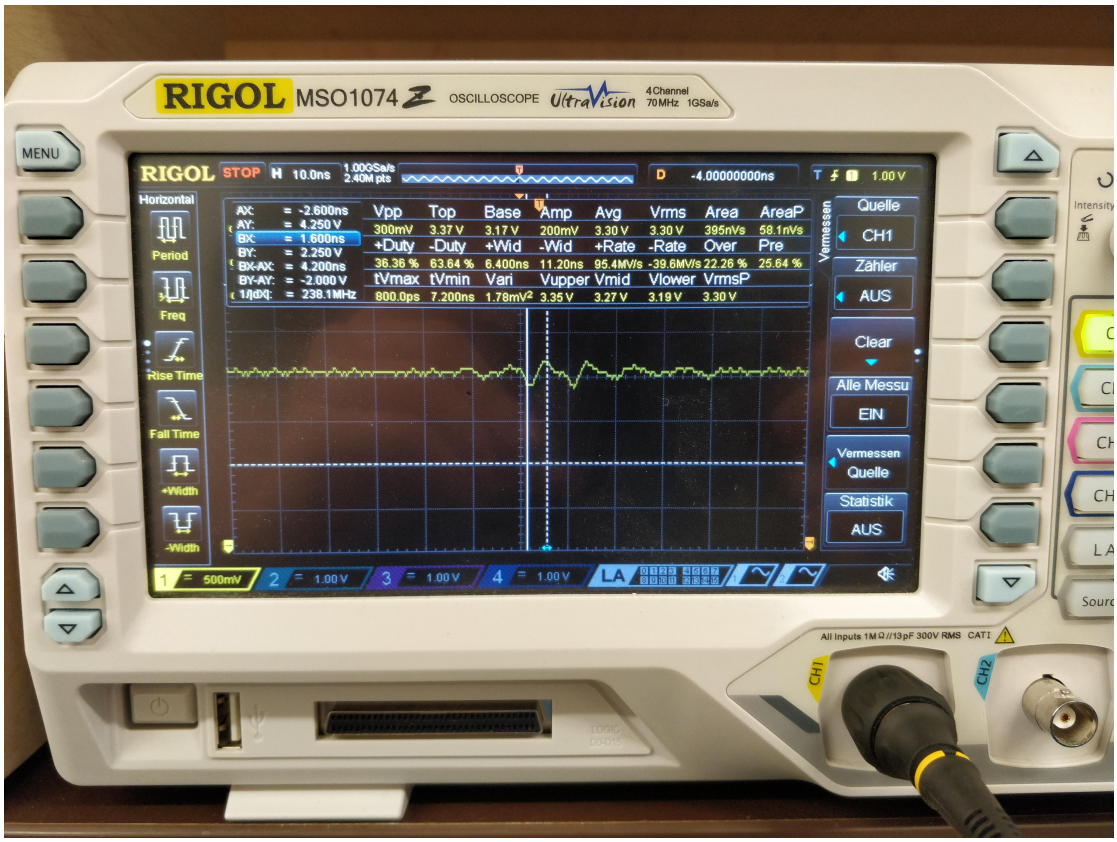

FIGURE 3.8: The 3.3 Volt line at the micro controller with an oscilloscope, when all valves get opened and closed.
The voltage-drop and -increase is at nearly 200mV with a pulse length of 11.2 nanoseconds

be felt by human users, with a voltage between 4.2V to 3.3V. The FIT0774 from DFRobot operates at 1.5V to 4.2 V and is small enough with a diameter of 10mm and height of 2.7mm. It only consumes 40mA on full load(R13, R14, R15, R17), which makes it well suited for the prototype.

- **Valves**
  The valves have to withstand the same pressure as the air pressure sensors, while being as small as possible. As mentioned in 3.5.2, this is a big challenge and the only small valves available currently, are 0520D valves from fspump with 3V. They receive more voltage than the nominal 3V, because they are directly connected to the battery with 4.2-3 Volt(R12) and consume up to 400mA each. Because these valves switch in negative pressure moments, contrary to other valves switching under high pressure, they can

open and close, without maximum power consumption.

- **Battery pack**
  The power is provided by a Turnigy 1200mAh 1S 1C Lipoly battery pack [64]. It is the same size as the space between the chambers and has nearly the same surface area as the components needed for the PCB. With a capacity of 1200mAh and a peak power consumption of 310mA while transmitting data over WiFi, 40mA while vibrating and an additional sporadic use of 400mA from the valves, the average power consumption is estimated at 400mA. With this assumption, the average up time the battery pack can provide is over 3 hours. This is more than an average training session and thus enough for the prototype.
  The battery pack is protected against short-circuits, under-voltage or over-charge. The maximum continuous discharge current is 1200mA. The theoretical maximum current draw peaks at about 1.6A for the valves, 200mA for the vibration motors, 310mA for the ESP32-S2, 3.7mA for the MPU6050 and two times 3mA for the pressure sensor. Totaling 2119.7mA and nearly double the continues rating of the battery pack.
  While operating normally, only two valves get activated at the same time and this only for a short period of time. The ESP32 will not need to send continuously and only have a power consumption of 30mA while not sending, spiking to 310mA when sending. On average, the system will have a power consumption of 170mA for the ESP32, 9.7mA for sensors, 100mA for motors and 100mA for the valves, adding up to a total of 379.7mA, which is below the constant current rating.(R6)

- **Voltage regulator**
  The voltage provided by the lithium polymer accumulator is above the maximum voltage of the ESP32. Therefore it must be converted to 3.3V. The gyroscope and air pressure sensor have to communicate with the ESP32 between 2.8V to 3.3V and need a stable voltage to measure consistent readings. The power-source looses voltage through discharging. The NCV8187[61] is a LDO Linear Voltage Regulator with good power output, that indicates if the voltage lies within its specifications. This prototype uses the NCV8187AMT330TAG that will generate 3.3V for the logic system. The chip can handle up to 1300-1750mA with a dropout

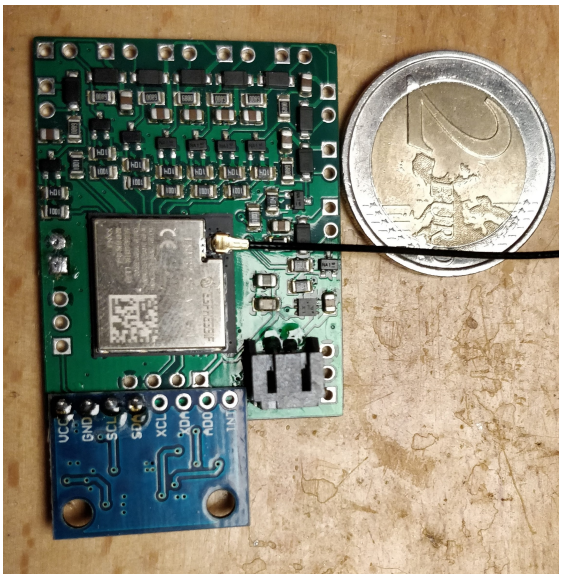

FIGURE 3.9: prototype PCB.
The ESP32 is in the center with the antenna connector, the blue PCB is the IMU(MPU6050) and on the top are the MOSFET Stages. The black battery connector is the power input for up to 5.5 Volts. The LDO is the tiny black chip above the connector and around this IC are the filtering components. The pressure sensors are connected through three vias each at the right and left bottom. The vias above the IMU are used for programming and the two solid vias in the middle left are for boot mode. All other vias are pairs of two for the motors and valves.

voltage of 150-220mV. The ESP32 will shutoff at about 2.8V and the lithium polymer accumulator at 3.0V with the voltage dropping nominally 150mV the regulator is perfectly using the whole battery capacity. The actuators will be powered directly from the power source.

- **Hot glue**
  For sealing and fixation purposes a glue is necessary. The glue has to be a multi purpose glue, as it is used on a wide range of materials, like TPU and metal. The company ”technicoll” produces a hot glue (9310) that is very fluid if molten and soft when hardened. Therefore it is optimal for flexible connections enduring stress and small gaps that have to be filled, like layer lines.

The PCB was created in KiCAD, an open source project , which is free of charge. The PCB can be seen in figure 3.9.

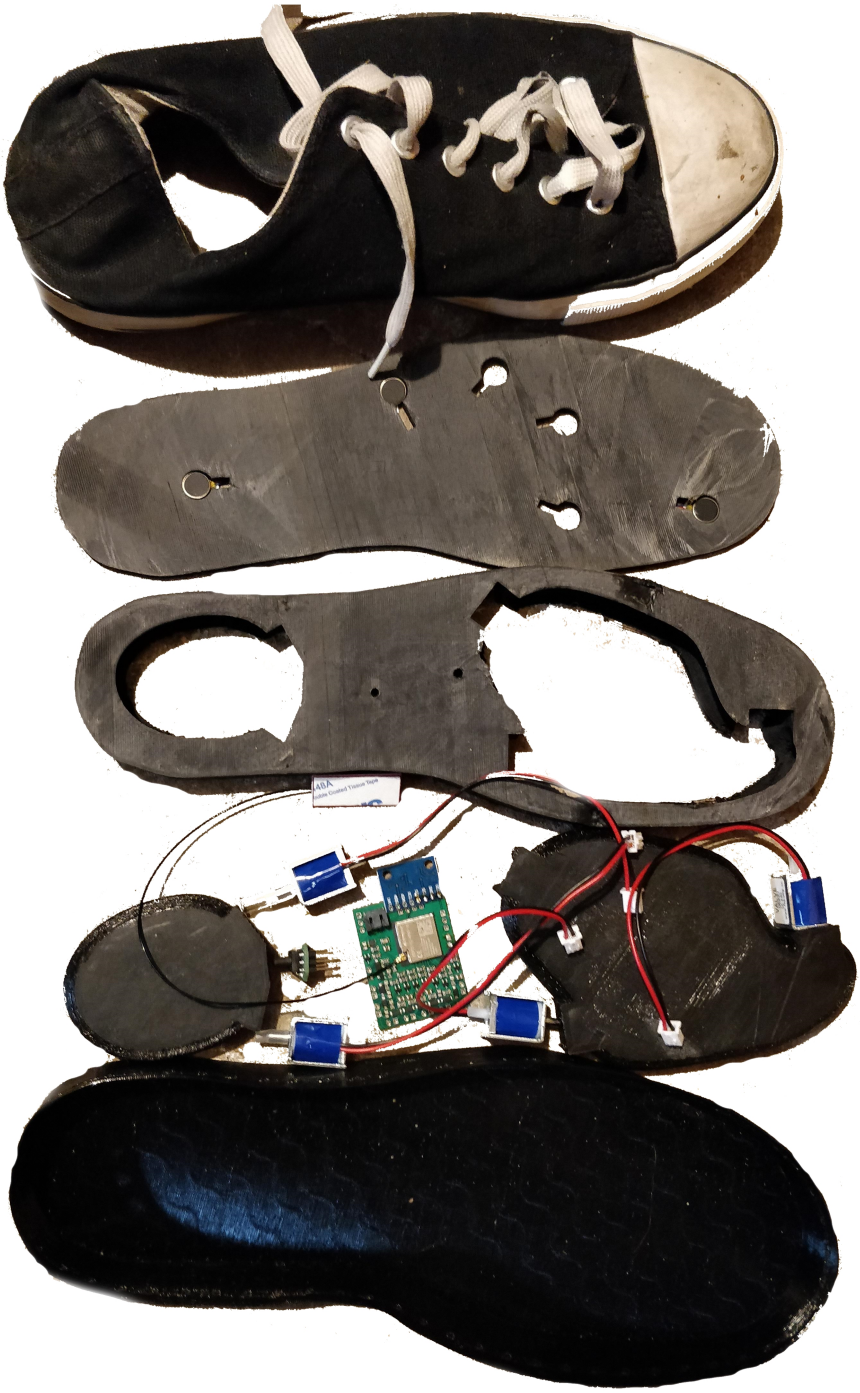

FIGURE 3.10: Final prototype in parts.
Top: Modified shoe with extracted sole
Second: vibration inlay with some vibration motors
Third: Inner shell, with holes for wires in the middle and space on the underside for the PCB, valves and battery
Fourth: pressure chambers in black, valves in an estimated position in blue silver, pressure sensor in green left to the PCB and PCB in the middle
Last: Shell of the system, this part connects with the modified shoe

3.6.2 Shoe

The shoe is housing all of the electronics and forms the connection to the user. This shoe is built out of four parts.

- Sole - The sole is the heart of the shoe, containing the pressure chambers and electronics. It is made from ninjateks "chinchilla" material. In figure 3.10 it is the object in the middle. The pressure chambers are from ninjateks "Ninjaflex" and can be seen under the sole.
- Insole - The insole is softer than the rest of the shoe and has holes for the vibration motors. This part has direct contact to the human foot. It is made of "Chinchilla" from ninjatek. It is the second shown object in figure 3.10.
- Shell - The shell contains the sole and on-top of it the insole, it has mounting holes for attaching the fabric of an existing shoe(R21). It is made from TPU V2 from dasFilament.
- Fabric - The fabric is recycled from a disassembled shoe.

All 3D printed parts are designed in Fusion 360, this offers a free educational and hobby license. The ninjatek filaments are often used in other papers, because of the well suited properties[19][33].

3.6.3 Software

One of the biggest parts of a hardware system with logic is the software. The software is implemented in Arduino and on the FreeRTOS of the esp32. The sensors are read every 10 ms, which is realised using the OS functions to ensure high quality read timings. FreeRTOS is often used in applications and papers with real time constrains[25][48][4][36]. The sensor collection and actuation of the active parts needs around 1.2 ms, from start to end. The reading from the I2C takes the longest with using more than 99 percent of that time. The I2C is in Fast Mode more than doubling the reading speed. The sensor data is uploaded directly via WiFi to the cloud time series database influx DB. This is realised

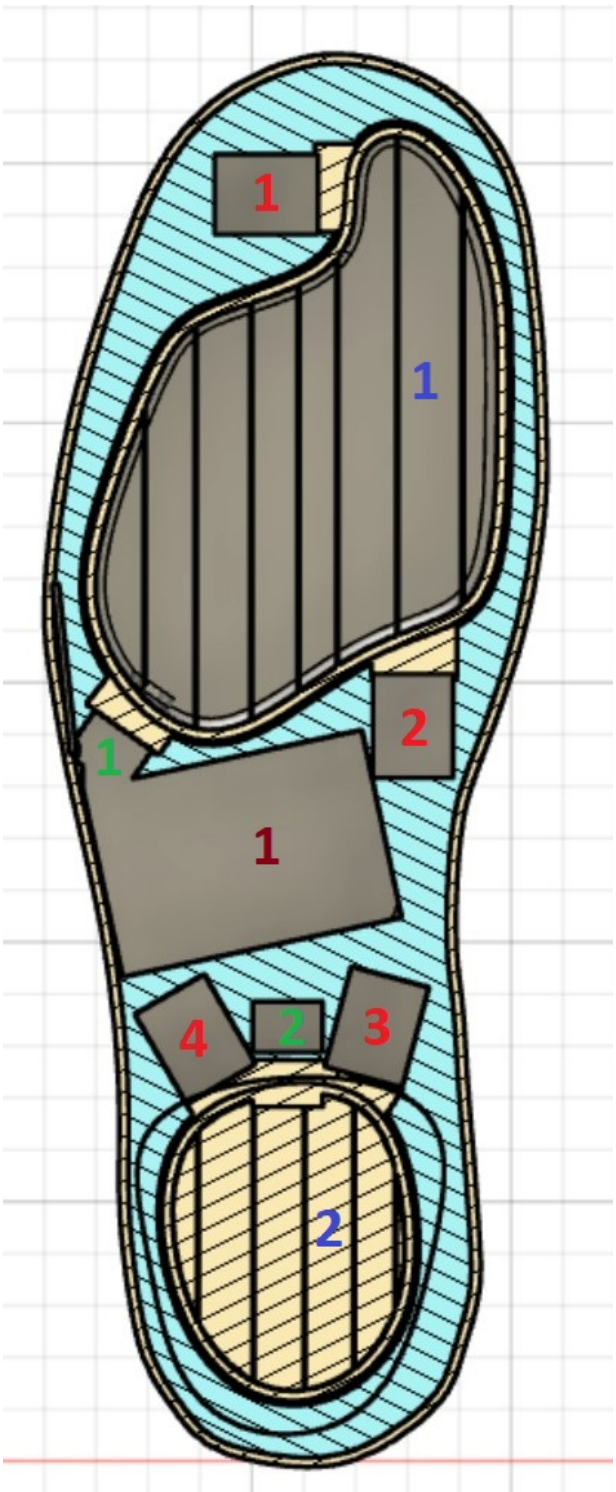

FIGURE 3.11: The cross-section of the CAD-Design
Slight blue: inner shell, yellow: Chambers with stabilisation stages, the blue 1 marks the front chamber and blue 2 marks the heel chamber, gray is space for components. Red 1 and 4 are air outtake valves, red 2 and 3 are the connection valves between the chambers. Green 1 and 2 are the pressure sensors, brown 1 is the space for the PCB and battery stacked on top. Above the green 1 on the left is a small dark line, this is the space for the external antenna.

with a low priority background task. A Web-server on the device can be used to update the system and control the functions and settings. A control plane is implemented to realise fast mode changes. Even without internet connection, the valve system and vibration-motors stay completely functional, only the collected data gets lost. The first 400 measurements will be saved in a system queue of FreeRTOS, with new data getting dropped if the queue is full.

3.6.4 Problems on the way

If the theoretical world collides with the real world there are many different known and unknowns problems that can occur. The first problem were the unreliable supply chains, caused by global crises. Parts not being in stock resulted in delays and unforeseen replacement of parts, for example in MOSFETS.
Another big problem was printing the airtight chambers. 3D printing is neither air- nor watertight, needing some fixes and special mechanics to improve the results. At the end, the chambers were printed in multiple parts, to seal the individual chambers airtight. They were prepared with an iron to close the biggest leaks, resulting in not fully, but mostly airtight chambers. The connections to the valves and sensors are critical, as they are stiff and thus break easily. A solution to this problem were more flexible tubes, that connect the chambers and valves/sensors.
The I2C connection was too slow and a SPI connection could prove to be the better choice. The tight timing collides with the wifi connection, but did not yet produce errors. Replacing I2C with SPI was not tested during this thesis, but may be inspected in future research.
When the Internet connection was too slow, the micro controller reset, because the RAM overflowed. An offline cache like an micro SD-Card could solve this problem in future research.
Another big challenge was integrating the power connection into an existing shoe. The PCB has no on or off switch and the deep sleep is not save enough since the battery is not disconnected. The next PCB will feature a MOSFET to switch off the connection to the Battery. Without this switch there is a need to disconnect the battery every time.
To change the battery when empty it needs to be replaced, an onboard charging

controller would improve the workflow. Because the inlay needs to be accessed often, the connection to the shoe has to be easily accessible and without generating much force on the stiff parts of the insole. While performing the procedure of accessing the inlay, the prototype got damaged a few times.
The electric and physical connections are not designed to withstand much movement. The vibration motors have managed to break their own cables, the pressure sensors can be pressed out of the shoe or tubes will disconnect, because of the curvature happening through use. With the help of hot glue most of these problems can be reduced or fixed. Reducing these issues may be focus of future research.

3.6.5 Recommendations & guidelines

Like mentioned in 3.6.4 there are quite some problems and limitations, that will be discussed in the next section. To avoid these problems, here are some guidelines and recommendations:

- Bigger problems need to be divided in smaller, more manageable pieces. This guideline can be used for all parts, soft- and hardware, as well as designing. For example, it was necessary to divide the prototypes in three focused prototypes and then merge them, to get the best results. Another example would be the chamber system, being divided in smaller parts and being therefore is much more reliable.
- To avoid harder work later, test every part individually and work from less to more detail.
- Explain to another person what and how you plan to do, before you start. This step can find potential problems and much easier solutions.
- While designing a PCB and software keep supply chains in mind and test parts for suitability.
- Document the progress instantly with images and text. To reconstruct something can be impossible or more work.

- Have a version control system, like git and keep old working designs, as the new one can be unsuccessful and rerolling to an older version necessary.
- Use silicon wires instead of normal wires, they are more flexible and produce less stress on joints.
- Plan with tolerances, measure tolerances and test the tolerances.
- Have a back-up part or spare parts. If something breaks or gets damaged the time needed for recovery shortens.
- Cables need space. The space for wires and cables has to be measured and planed. If something has to be removable, the wires will need some space to move.

3.7 Requirement Check

At the end the different prototypes were combined to one. It has size EU42, therefore R1, R2, R18, R19, R20, R21 and R22 have been met. The FreeRTOS will satisfy R3 through its system delays and prioritizing. The Wifi connection will upload every 500ms and needs about 700-800ms, which means, that R4 is met. R5 was tested with a scale and the pressure sensor can't measure the values, but can withstand the required force. The valves are tight and with added hot glue the sensors don't come loose, meaning that R5 is also met. With a maximum power consumption of 2119ma the system will work for over 30 minutes, however the maximum power consumption cant be delivered, if the maximum power draw of the battery management system (BMS) is delivered, the system will work for approximately an hour. The average power consumption will work for over 3 hours, meeting R6. The chambers can inflate and bloat up to nearly double their original height, also being able to compress to nearly touching the top and bottom surface of the chamber. The damping on high pressure is less than on medium, meeting R7. R8 and R9 are met because of the two valves for each chamber, as can be seen in figure 3.11. R10 is met, as the pressure is falling relatively constant, pictured in figure 3.13, the value is 880 over normal and is falling by 184 (20.91%) in 11 seconds. R11 is met, like shown in figure 3.12.

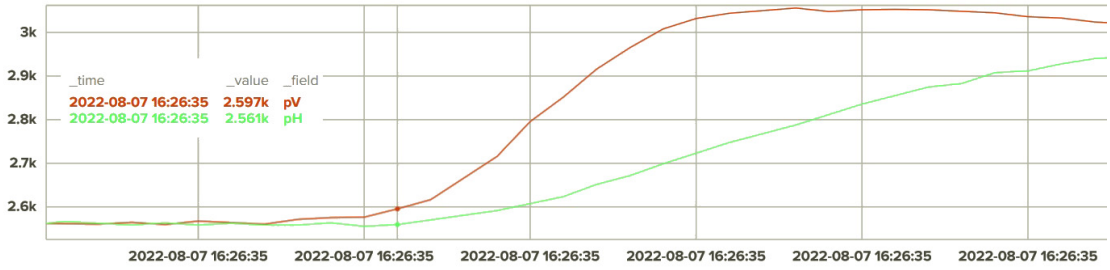

FIGURE 3.12: Pressure change between chambers.
The dot marks the threshold detection when the valves get the signal to open. The pressure increases instantly, nearly linear.

The prototype was set to a threshold of 20 out of 4096 analog values (approximately 14,6mV) to connect the two chambers. The values immediately start growing nearly linear, when the threshold value has been exceeded. R12 is met, because none of the chambers or sensors get damaged by applying over 2000N of force. The measurement was taken with a scale and measured 150kg (1472 Newtons). The sensor can withstand 600kpa, while 300kpa can be measured. The Vibration System can vibrate noticeably and thus meets R13. The vibration motors need space to function and if the insole is too compressed, the vibration is minimized, but with the used insole the vibration stays noticeable. With the MOSFET Stages every motor can be controlled with a PWM signal, this meets R14 and R17. The MOSFET can power the 40ma without getting warm and the battery can deliver enough power to vibrate all motors continuously for more than 1 hour, exceeding R15. The arrangement in R16 can be seen in figure 3.10. Therefore all requirements are met and the prototype is a success.

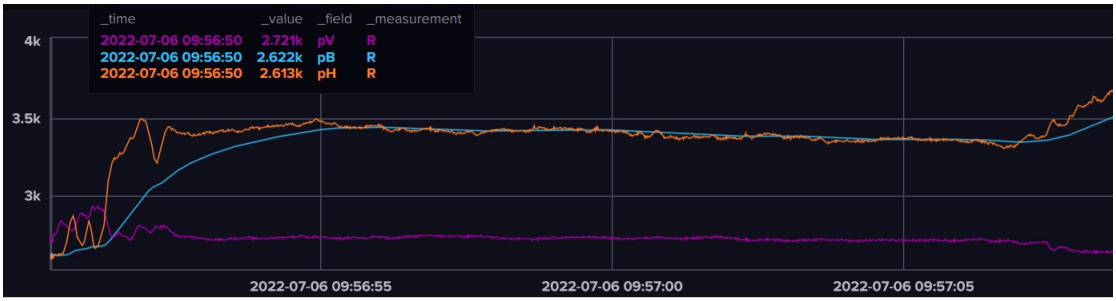

FIGURE 3.13: Pressure fall over more than 10 seconds in the heel chamber. The orange line is the pressure in the heel chamber, the pressure is falling by nearly 20% of the gained pressure.

4 EVALUATION

If you think user research is expensive, you should look at the cost of building the wrong thing.

– Mario Maruffi[49]

4.1 Study Design

To continue validating the research question Q1 (”s it possible to build a smart shoe, with pneumatic actuation, within a normal form factor?”) and Q2 (”Is it possible to build an smart shoe, that can simulate different terrains?”), there are three separate evaluations, each with their own hypothesis. The first two are internally validated by other study’s and they will externally validate the third study for robustness. If the prototype presented in this thesis can validate the findings of the other studies they can be reproduced on another external laboratory from other researchers and using different prototypes.
Because the last evaluation regards a new field without a comparable study, the internal validity has to be proven.

4.2 Robustness evaluation: Underground detection

The main goal in this evaluation is to reproduce the findings of the paper ”CapSoles: who is walking on what kind of floor?” [50], especially ”In general, the sharpness of separation between hard and soft floors can be considered as easily distinguishable.” (Q4) and ”[...]soft surface [that] caused many random irregularities” (Q5). If this prototype can reproduce these two findings, they can be seen as externally validated in robustness.

4.2.0.1 Hypotheses

Taken from the learning of ”CapSoles” [50] two hypotheses can be formed:

- (H1) ”It can be assumed that this prototype can differentiate hard and soft undergrounds.”
- (H2) ”The consistency of measured values on hard undergrounds is higher, than on soft undergrounds.”

4.2.0.2 Apparatus

The device in this evaluation is the combined prototype with two pressure chambers as well as pressure sensors. The vibration and valve system will be deactivated. The sensor system has an IMU and sends data from all sensors into the cloud influx db within 10ms intervals. The prototype from ”capsoles”[50] has some differences, like capacitive sensors and includes neither accelerometer nor gyroscope. The sample rate further differentiates the prototypes, as this prototype has a sample rate of 100Hz and the prototype from ”capsoles”[50] samples at a rate of 30hz.

4.2.0.3 Procedure

The evaluation procedure starts with explaining the task, as well as the needed data collection, to the male or female participant. After this, they will put on the prototype and make a few steps, getting a feel for the shoes and the wear. The steps are used to check the prototype for functionality issues. The participant than starts the task, that is described in the next section. After the test on the first terrain the procedure will start again in another location. The participants will walk on randomised terrains over the course of a few days.
The measured terrains are from soft to hard: sand, grass and asphalt.

4.2.0.4 Task

The participant will walk straight on the terrain for 10 meters and then turn around and walk the same path back to the start.

4.2.0.5 Participants

The chosen participants must have a foot size between 39EU and 42EU. the stats for the 3 participants are:

- Female, 21 years, 82kg, 163cm, 39EU
- Male, 27 years, 76kg, 178cm, 42EU
- Female 43 years, 90kg, 170cm, 40EU

4.2.0.6 Data Gathering Methodology

The pressure sensors measure the air pressure in the chambers, the values can be used to find the ground contact. The IMU collects accelerometer and gyroscope data for 3 directions. With this data, the foot movement can be measured. The total measuring acquisition length is about 0.7ms. To analyse the data and validate the hypotheses, it will be searched for random irregularities. These irregularities indicate a soft underground if the hypothesis H2 is correct.

FIGURE 4.1: Measured values of the three undergrounds.
Top: Asphalt, Second: Grass, last: Sand.
pH: Pressure Heel, pV: Pressure Ball, pB: pressure Baseline, ax: accelerometer X, gz: Gyroscope X, ay: accelerometer Y, gy, gyroscope Y, gx: gyroscope X, az: accelerometer Z

4.2.0.7 Results and Discussions

The most interesting part of the evaluation was the foot to ground interaction. The phase where the foot is still on the ground was most classifying, because the stability of the foot changed with each terrain.
The analysed data can be seen in figure 4.1. The first graph shows the standing phase on asphalt. The measured values on asphalt appear nearly stable. The second graph shows grass, the values less stable compared to asphalt. The last one shows sand, demonstrating big unstable measurements. An easy threshold classifier on the signal ripple can differentiate the samples with a 100% accuracy, if the samples are cleaned up like followed. The first and last two steps are incomplete and not used. Standing phases and the turn around gets removed. The sample size was small with only three different participants and two 10 meter long walks on the different terrains. However, this evaluation showed that the system can differentiate between diverse undergrounds by the stance time. On soft undergrounds, the stance times are longer (sand 800ms, grass 730ms), than on hard undergrounds (asphalt 670ms). The hypotheses H1 ”We

assume that this prototype can differentiate hard and soft undergrounds.” can be accepted, because the ripple is measurable higher. The hypotheses H2 can be accepted as well, as the ripple on soft underground is much more inconsistent than on hard asphalt.
Therefore, the robustness of Q4 and Q5 in ”CapSoles: who is walking on what kind of floor? ”[50] can be proven.

4.3 Robustness evaluation: User actuation

The main goal in this separate evaluation is to reproduce the findings of the paper ”mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles”. [51]. In particular the hypothesis 5 from ”mobiLLD”[51]: ”Augmenting vibrotactile feedback under the foot alters gait.”, that was proven in ”mobiLLD”[51]. To reproduce this finding and validate the robustness, the combined prototype can be used.

4.3.0.1 Hypotheses

The first hypothesis for this evaluation is the same as in mobiLLD[51]: (H3) “Augmenting vibrotactile feedback under the foot alters gait." The second hypothesis is: (H4) “With vibrotactile feedback the stance time will be increased.”. Hypothesis (H5) is: ” Stronger vibrotactile feedback will increase the stance time.”. The last hypothesis is a finding from ”mobiLLD”[51] (H6): ”The IMU will be affected from the vibration motors.”, because the IMU data cant be used in ”mobiLLD”, because of the interferences.

4.3.0.2 Apparatus

The combined prototype will be used to generate data, which is used to answer the hypotheses. The chamber system will be deactivated, meaning that no air pressure will be changed, but the pressure sensors are still active. The IMU collects data with a frequency of 100Hz. The vibration system is active and will be

used for the evaluation. The prototype is alike to the one from "mobiLLD"[51], but built using a different TPU and less pressure zones and vibrations in the insole. Both prototypes feature the same sample rate at 100Hz , however the frequency of the vibration motors is 1500Hz and not 2000Hz like in mobiLLD.

4.3.0.3 Procedure

The procedure starts with an explanation of the task to the participant and the agreement of data collection, then they will put the prototype on and can walk some steps to get in touch with the feeling. Like in section 4.2, this steps will be used to check for functionality issues. The participant then start the task in mode 0 (no vibration), repeating it three more times in different modes, until all 4 modes are tested. The four modes are: (0) no vibration, (1) random vibration, (2) full vibration, (3) vibration with gait. The path is the same in every mode and for every participant.

4.3.0.4 Task

The task is nearly the same as in subsubsection 4.2.0.4. The participant walk straight on linoleum flooring for 10 meters and then turn around and walk the same path back to the start.

4.3.0.5 Participants

The chosen participants must have a foot size between 39EU and 42EU. There are three different participants:

- Female, 21 years, 82kg, 163cm, 39EU
- Male, 27 years, 76kg, 178cm, 42EU
- Female 43 years, 90kg, 170cm, 40EU

4.3.0.6 Data Gathering Methodolog

The pressure will be at a medium pressure level within the prototypes possibilities, with the pressure sensors generating the needed ground touch detection. The gait can be measured using only two chambers, because the analog values of the pressure can be analysed and the phases can be reconstructed using a threshold. With this pressure sensor the stance time can be reconstructed and the vibration system is only active if the shoe has contact to the ground. A python script with a threshold calculates the stance time. The IMU will be active and generate data. The data is used to answer H6, by comparing the values with and without vibration.

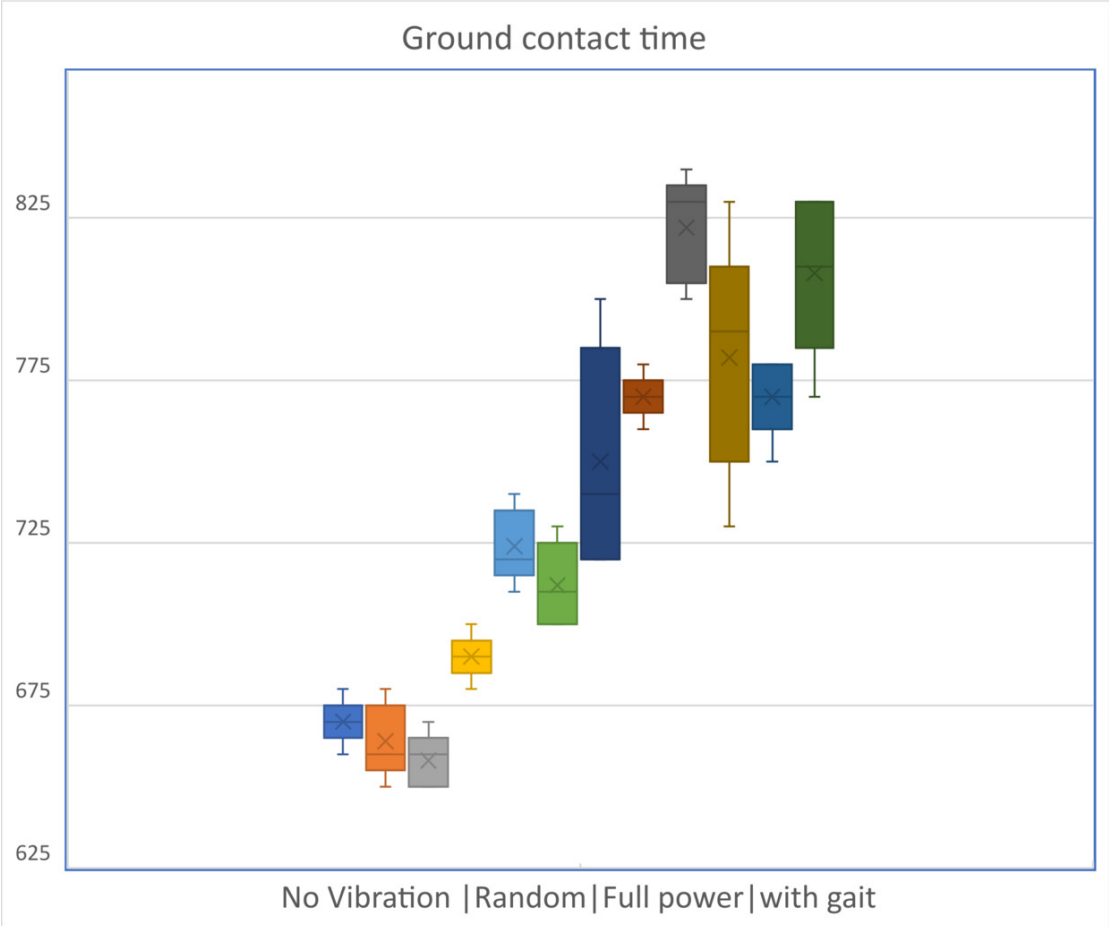

FIGURE 4.2: Ground contact time of the three participants. No vibration has a lower stance time than random vibration. Full vibration with or without the gait has the largest stance time.

4.3.0.7 Results and Discussions

The ground detection was realised with pressure readings. The data, generated from the python script, is shown in figure 4.2.
The results in figure 4.2, show the same five steps of the track taken by the three participants. The results show the ground contact time in milliseconds. The base standing time without vibration lays between 641ms to 658ms. With random vibration strength, changing every 10ms, which is nearly equal to half of the possible vibration strength, the standing time is increased to between 690ms to 724ms, averaging to 67ms more time spent standing. The full strong vibration of the motors will stretch the standing time to between 750ms to 822ms and the full vibration with the walking movement has increased from 770ms to 808ms.
This evaluation comes to the same conclusion, that the standing time increases with vibrations. This illustrates, that this actuation can change the walking of the participants and validate H1, H2 and H3.
To validate H4, the IMU Data has to be analysed, the results are shown in figure 4.3. The signal clearly gets changed by the vibration motors. The soft vibration from the random vibration strength is less obvious, but full strength is easily visible.
Interesting was, that the stance time with no vibrations on asphalt(650ms), grass(720ms) and sand(800ms) from the first evaluation are nearly the same stance times as no vibration(641ms-658ms), random vibration(690ms-724ms) and full vibration(750ms-822ms) in this evaluation. An assumption is, that vibration and softer undergrounds make the participants uncertain and the persons take more time to stay until they feel save and stable. All hypotheses are validated and therefore the robustness of the result in ”mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles”[51] can be proven.

FIGURE 4.3: Measured values of the 4 modes.
Top: No vibration (0), Second: Random vibration (1), Third: Full power (2), Last: with Gait (3).
ax: accelerometer X, gz: Gyroscope X, ay: accelerometer Y, gy, Gyroscope Y, gx: Gyroscope X, az: accelerometer Z

4.4 Internal Validity evaluation: Simulating different terrains

With all the produced knowledge it is possible to conduct a study about terrain simulation. Because simulating terrain with cushioning and vibration is not been researched jet, this approach has to be validated. The Construct Validity and Empirical Replicability both have to be proven. The Empirical Replicability is

given by the amount of participants, as they provide statistical evidence. This evaluation is inspired by ”Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study”[85], but in a smaller scope with less sensor systems and a focus on realism, shown in figure 12 within the mentioned paper. The used AR/VR System however is completely different, because this evaluation will use an Oculus Quest headset[60] with a video of a terrain and the other study uses a VR cave[16] with treadmill and a gaming environment. The sensing part from the mentioned paper with cameras and other sensors are not relevant for the realism research.

4.4.0.1 Hypotheses

The first Hypothesis is: (H7) ”Soft terrain can be simulated on hard terrain, by gaining a value above 5 on a scale from 0-10 as rated by the participant” and the second Hypotheses (H8) is ”The simulated terrain is in average more realistic, gaining a value above 5 on a scale from 0-10 as rated by the participant”

4.4.0.2 Apperatus

The combined prototype will be used for this evaluation. The Web-server is active and controls all other systems. The data upload is not necessary, as the vibration from the motors interferes with the IMU data. Valve and vibration systems are active. The VR-Headtset is an Oculus Quest[60] showing self produced videos. These videos have been produced using a 360° camera, the Insta360 ONE R twin edition[42] and some of the footage can be seen in Figure 4.4.

FIGURE 4.4: Visualisation from three of the Videos. The first one was captured on sand, the second on asphalt and the last one on grass.

4.4.0.3 Procedure

The participants will give the permission to collect data and then the procedure will be explained. The used scale with 0 being the worst, 5 being neutral and 10 being the best possible score gets explained. The Oculus Quest[60] will be set to the Youtube playlist with all terrains. The participant will be placed in the middle of a linoleum floored room and puts on the VR-Headset[60]. They will adjust it to their needs. Having fulfilled all preliminary steps, the user goes to the edge of the movement radius where they can choose one terrain. The prototype will be set to the pressure of the chosen terrain and the user has to walk in one place to generate the needed pressure. Then they can press play on the video and the prototype will be set to the terrain mode. The terrain mods are:

1. Asphalt (Hard pressure value and short vibration on first hit)
2. Grass (medium pressure, but the Chambers are connected and soft vibration on the whole stance time)
3. Sand (low pressure and some really light vibrations)
4. Linoleum (medium pressure, no vibration)
5. gravel (medium pressure, random hard vibration)

The participant will follow the instructions of the instructor in the video and answer the questions from the instructor in the video. Then they have to repeat the process on all other terrains. After all terrains, the participants can remove the Oculus Quest and will repeat all undergrounds in an random order with the same questions from a real instructor.

4.4.0.4 Task

The task of the participant is to follow the directions of the virtual or real instructor. They have to look around, then go two steps and stop. After this, they will be asked four questions:

1. How realistic was the terrain on a scale between 0 to 10?
2. On what kind of terrain were the steps taken?
3. How difficult was it to walk?
4. How different is the shoe to the previous run on a scale between 0 to 10?(normal shoes in first run)

4.4.0.5 Participants

There are 20 Participants with an foot size between 38-42EU and a height between 158cm to 192cm and a weight between 65-98kg from different genders. The age lies between 22 and 54 years. Some off the participants have experience in AR/VR.

4.4.0.6 Data Gathering Methodology

The data needed to validate all remaining hypotheses is gathered, by asking participants the aforementioned four questions and evaluating their answers.

4.4.0.7 Results and Discussion

While it was planned to let the participants walk 10 meter per terrain, a change in the final evaluation had to be made. In this the walk is defined as two steps, because of two reasons:

1. The Oculus Quest only allow to move one meter in video mode, to reduce injuries (after conducting the evaluation, this fact was patched).
2. The participant should only communicate their first impression.

Two participants had to repeat the process, because the vibration system was accidentally turned off in some terrains. The results of realism with VR can be

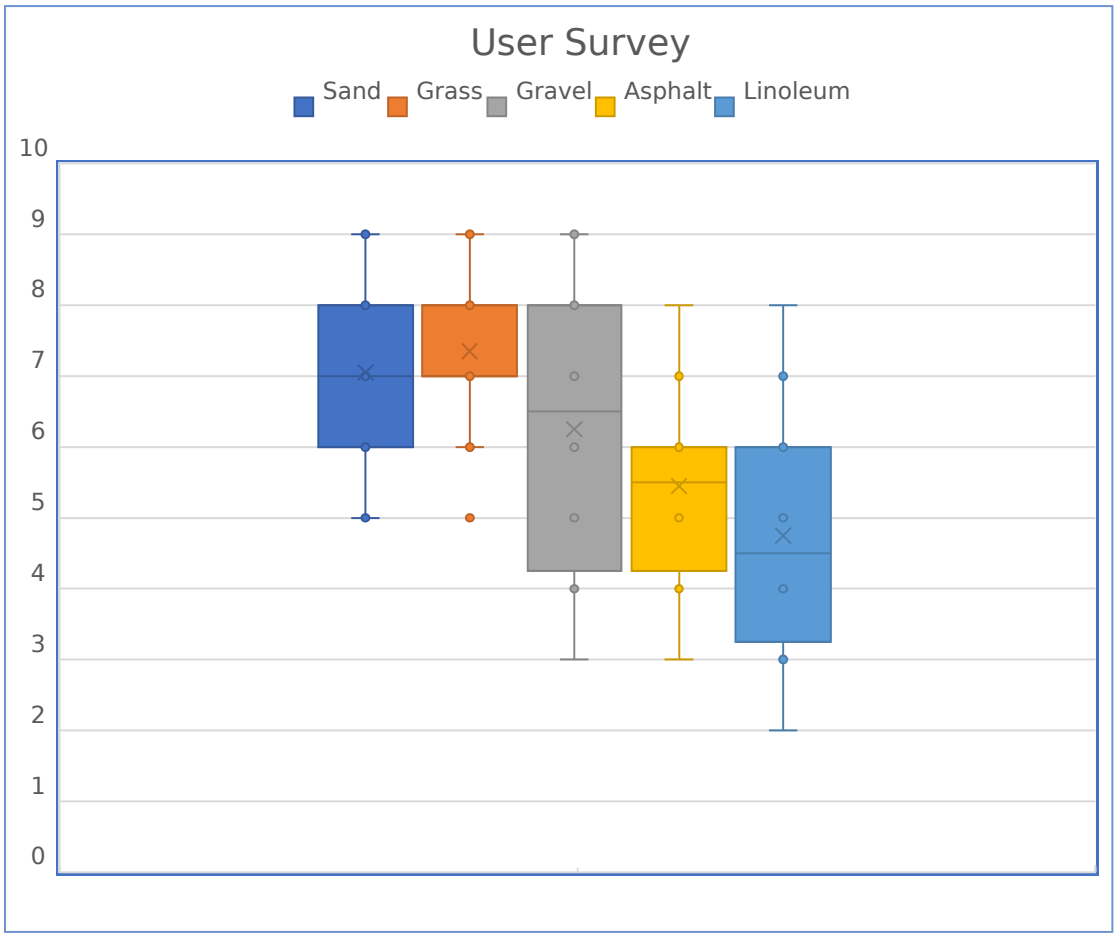

FIGURE 4.5: Results of the user study for realism of the terrain. 0 is equivalent to not realistic and 10 to fully realistic. Sand, grass gravel and asphalt are more realistic than five, only the real non actuated underground Linoleum is below five.

seen in Figure 4.5. Interesting is the fact, that hard undergrounds have a worse score compared to soft undergrounds, although the tests are conducted on hard underground. Grass has the best score and sand the second to best. Gravel has a wide range. The original terrain Linoleum is unexpectedly rated the worst. H7 can be validated with the score of about 7 which is above 5. H8 is harder to answer, because the simulated terrains all get a score slightly over 5 but the original terrain, which is not simulated, a score slightly under 5. This shows, that the shoes have a weakness to be stiff without bubble up. Nevertheless, H8 can be proven with constrains of the none simulated base terrain.

With a more scientific approach an analysis of variance (ANOVA)[80] was used

to search for significant differences. The one-way ANOVA ($F(4.95)=11.07$; $p<0.01$) showed a significant difference, with an p-value of 0.000000205. Because of this significance a Post-Hoc-Tests has to be performed. For this, a pairwise t-Test was performed for each terrain.

- Sand vs Grass
  A post-hoc analysis performed by a paired sample t-Test ($T(19) = -0.77$, $p > 0.01$) yielded **no** strong statistical difference between Sand ($M = 7.05$; $SD = 1.31$) and Grass ($M = 7.35$; $SD = 1.50$). The two-way-p-Value with Bonferroni correction is 4.52.

- Sand vs Gravel
  A post-hoc analysis performed by a paired sample t-Test ($T(19) = -0.77$, $p > 0.01$) yielded **no** strong statistical difference between Sand ($M = 7.05$; $SD = 1.31$) and Grass ($M = 6.25$; $SD = 3.57$). The two-way-p-Value with Bonferroni correction is 0.841.

- Sand vs Asphalt
  A post-hoc analysis performed by a paired sample t-Test ($T(19) = -0.77$, $p > 0.01$) yielded **strong** statistical difference between Sand ($M = 7.05$; $SD = 1.31$) and Grass ($M = 5.45$; $SD = 1.63$). The two-way-p-Value with Bonferroni correction is 0.00266, with an strong effect size ($1.182>0.8$)[20].

- Sand vs Linoleum
  A post-hoc analysis performed by a paired sample t-Test ($T(19) = -0.77$, $p > 0.01$) yielded **strong** statistical difference between Sand ($M = 7.05$; $SD = 1.31$) and Grass ($M = 4.75$; $SD = 2.62$). The two-way-p-Value with Bonferroni correction is 0.000144, with an strong effect size ($1.417>0.8$)[20].

- Grass vs Gravel
  A post-hoc analysis performed by a paired sample t-Test ($T(19) = -0.77$, $p > 0.01$) yielded **no** strong statistical difference between Sand ($M = 7.35$; $SD = 1.50$) and Grass ($M = 6.25$; $SD = 3.57$). The two-way-p-Value with Bonferroni correction is 0.356.

- Grass vs Asphalt
  A post-hoc analysis performed by a paired sample t-Test ($T(19) = -0.77$, p

> 0.01) yielded **strong** statistical difference between Sand (M = 7.35; SD = 1.50) and Grass (M = 5.45; SD = 1.63). The two-way-p-Value with Bonferroni correction is 0.00246, with an strong effect size (1.245>0.8)[20].

- Grass vs Linoleum
  A post-hoc analysis performed by a paired sample t-Test (T(19) = -0.77, p > 0.01) yielded **strong** statistical difference between Sand (M = 7.35; SD = 1.50) and Grass (M = 4.75; SD = 2.62). The two-way-p-Value with Bonferroni correction is 0.000503, with an strong effect size (1.456>0.8)[20].

- Gravel vs Asphalt
  A post-hoc analysis performed by a paired sample t-Test (T(19) = -0.77, p > 0.01) yielded **no** strong statistical difference between Sand (M = 6.25; SD = 3.57) and Grass (M = 5.45; SD = 1.63). The two-way-p-Value with Bonferroni correction is 1.189.

- Grass vs Linoleum
  A post-hoc analysis performed by a paired sample t-Test (T(19) = -0.77, p > 0.01) yielded **no** strong statistical difference between Sand (M = 6.25; SD = 3.57) and Grass (M = 4.75; SD = 2.62). The two-way-p-Value with Bonferroni correction is 0.227.

- Asphalt vs Linoleum
  A post-hoc analysis performed by a paired sample t-Test (T(19) = -0.77, p > 0.01) yielded **no** strong statistical difference between Sand (M = 5.45; SD = 1.63) and Grass (M = 4.75; SD = 2.62). The two-way-p-Value with Bonferroni correction is 0.398.

Question two was worded poorly, which resulted in the participants describing the sensation they encountered instead of guessing what kind of underground they were walking on. Soft undergrounds was described as soft and hard as hard, the gravel was often described as sandy and uneven. Linoleum was once described as sandy two. This categorisation proved to be informative nonetheless, since it allowed for a deeper understanding of the actual sensation.

Since the order of the terrains the participants encountered was randomised, results were hard to compare. The participants tended to use the first encountered

terrain as baseline, to which they compared the following ones. Depending on the used baseline, the results differed greatly, which is why they are not going to be used. In future research, instead of asking for a number rating, it would be beneficial to compare the difficulty or ask for problems.

Comparing different simulated terrains pairwise with this amount of users is not statistical. The fact, that the difference when switching from a soft to a hard terrain or vise versa is rated with a 9 or 10 by every user is an interesting finding. It shows that a relevant change in the shoe sole can be induced.

In addition to the asked questions, the communication with the participants showed in general, that the vibration feels weird at first glance and irritates, if they are to strong, which was the case during these experiments. Some of them are surprised by the wide range of change of the prototype and the ability to simulate grass and sand.

4.4.1 Recommendations & guidelines

Some take aways from this experience are the following:

- Test the evaluation before the real evaluation, this helps to find errors and train the procedure.
- Plan with spare time, a evaluation can take longer, because of breaking hardware or difficulty's with participants. A talk with the participants after the procedure can gain more data for an later evaluation.
- Questions have to be clear defined. The Participants don't have to ask something to clarify.
- You can pre recorde single questions in a VR setup, but then you need a trigger to start the record.

5 DISCUSSION

In this paper a prototype and a survey contribution has been conducted. The prototype was able to validate other papers and to simulate terrains. The research questions can be answered. Research question Q1, "s it possible to build a smart shoe, with pneumatic actuation, within a normal form factor?", can be answered with ”yes, it is possible”. One investigated paper [70] created a prototype that is contained within a shoe. Others[68] are small enough to be placed within one. The prototype from Chapter 3 has a big pneumatic actuation system and is still in the form factor of a normal shoe, therefore Q1 can be answered with "yes, even a large pneumatic actuation system fits in the shoe form factor” The terrain simulation was explored for one terrain in another paper[85]. This thesis expanded on that by simulating 5 different terrains. Therefore Q2 can be answered with ”Yes smart shoes can simulate different terrains”. With this prototype it was possible to change some properties, like the cushioning and damping of the sole. Vibration can simulate interaction with the terrain, by giving short impulses and simulating the motion from small stones, that are moving under the users feet. Simulating smart foot wear is usable in a wide range of tasks, some of them include:

- Studies with more sensors
  Like in other studies[84][85][50][57] the sensor system can be evolved to include for example camera systems or motion tracking[2]. More IMUs

can be used to get precise measurements of changing properties and track the user even more precisely. The Gait analyse can show which properties must change to generate the wanted gait.

- Training of changing undergrounds
  If a person will run on changing terrain, the risk of injury can be decreased, by training the body with the shoes on them. A study which explores whether training humans on different terrains can reduce the risk of injury[13] shows promising results. This study shows that the injury rate can be decreased with training. Unfortunately the effect reduces over time without training. Using a simulating smart footwear could reduce the risk of injury even further, since the trainee would not be required to run on the dangerous terrain.

- VR/AR
  This prototype can be used as input and output device for VR and AR. Therefore an API has to be implemented. Examples of an field of use for smart wear would be the metaverse. For the big dream of meta with the metaverse, more interfaces to integrate the user into the metaverse[87] are needed. An adequate pressure value of the foot can be used in games to trigger different events, like breaking things, walking or even sinking into sand. Actuation like in "Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study" [84][85] can be implemented to give the user more feedback and a better experience of the terrain.

- Energy harvesting
  With the chamber system an energy harvesting solution is possible, there are some papers describing this approach[3]. This could be integrated with a fine adjustment of properties, making the shoes self sufficient, as the energy of the ground reaction force is huge compared to vibration or temperature harvesting approaches[39].

- 3D Profile
  This prototype showed that is is possible to inflate chambers changing the properties of the shoe, but it would also be interesting inflating the shoe profile to bulge in the direction of the ground, reducing or increasing the

FIGURE 5.1: System from Nike with 3D-Printed cleats[5].

slip. Different to the simulation of the underground[85], a reaction to the environment and the adjustment of properties can result in a big advantages for the human. Different shoe profiles and expandable cleats can improve the stability[72]. Nike uses 3D printed cleats that can't change, but can be replaced by printed ones[5]. If the cleats could change themselves on the fly this would pose a big advantage. This system can be seen in Figure 5.1.

5.1 Key insights

In the following the key insights of developing this prototype are explained and evaluated.

1. **Pressure chamber material** FDM 3D-Printing is not feasible for airtight pressure chambers, without using different post processing like melting the surface smooth and air tight or coating the surface with another material, like rubber paint. The 3D printer's function to iron a print itself is not sufficient.

2. **Type of insole material** The new Chinchilla TPU is a great material for an impressible layer in a shoe, because it is very soft. The damping can be adjusted in finer detail, if the material is softer and the infill pattern effect decreases.

3. **Microcontroller** The ESP32 is a well designed microprocessor making it perfect for an IoT device. Even in deep sleep the ESP can take measurements, saving them to a SD Card or flash storage. In normal mode, uploading the data if a connection is present is possible. FreeRTOS is strongly recommended, because of the real time features like precise timing functions and the scheduler. System Queues can be used to guarantee consistence in data of independent program tasks.

4. **Simulating terrain with cushioning and vibration** It is possible to simulate terrains with a cushioning and vibration prototype and visual stimulation to a certain degree. The study shows that two chambers, that are connected and change the pressure, are especially helpful in simulating while vibration needs more work, as it is difficult to dose.

5. **Identifying gait cycle with pressure chambers** It is possible to reconstruct the gait cycle with two pressure chambers as well as with pressure sensitive insoles. The two chambers with sensors need adjustments, because the pressure has to be mapped to the surface, but with this in mind the analog pressure can be mapped to the gait cycle.

6. **Wireless data upload** It is possible to stream an 100Hz signal of 9 values over WiFi to an InfluxDB server with https on the ESP32 with an one second delay. This is only possible, if the upload is consistent, with only one delay of one second, because in case of a connection problem, the upload cant keep up. The upload normally needs about 700ms to complete, nearly without a difference in size of the package. The package size is limited by the limited resources of the micro controller.

7. **WiFi is fast, but has a limited range** For a genuine product WiFi is the wrong technology. The range is limited and the power consumption is high. In an environment where live data has to be accessed over the internet, a 5G approach features better connections and in a normal environment the

data can be collected and uploaded at a later point in time or streamed over bluetooth to a smartphone with internet connectivity.

8. **Ripple reduction** The electric noise from inductive loads on the power line of the micro controller can be reduced with a MOSFET-Stage, consisting of diodes, resistors and capacitors, presupposed the actuator only has one direction.

9. **Power stabilisation** Using the full potential of a protected 3.3V LiPo-Akku, without fluctuations that would render analog sensor data useless, is possible due to a LDO, with a dropout of around 200mV. This requires the micro controller to work with 2.8V to 3.3V. Analog measurements are compared to supply voltage (VCC) and can hence be interpreted accurately.

10. **Vibration alters the gait speed** With increasing vibration the ground phase will increase. The paper ”mobiLLD”[51] has shown that it is possible to alter the stance time, this can be reproduced with the presented prototype. The correlation between vibration strength and delay in stance time is not clarified.

11. **The terrain alters the gait speed** With softer terrain the ground phase will increase. The stance time was increased on grass over asphalt and even more increased on soft sand.

12. **Vibration increases noise on IMUs** Vibration in an object, like the sole of a shoe, will be detected from an IMU and the vibration can make the reading of other movements difficult.

13. **Vibration fixation** Motors have to be fixed in place, because the cable will break otherwise. The vibration motors have to be connected to a fixed point or the cables have to be fixed to the motor, so that they only move directly with the motor. Still, the motors need to be loose enough for producing vibration. Very soft hot glue can fulfill both requirements.

14. **Questions with values between 0 and 10 are difficult** The participants have trouble to remember the orientation of the numbers and are careful with an unknown range of possibilities, therefore they will pick numbers from the center at first and don’t use the edges 0 and 10 if there is another option left.

15. **VR survey** Participants may have questions or need more time to answer than approximated. Therefore a pre-recorded video with the questions is sub-optimal. Standing behind them and asking the questions in real live is more convenient.

16. **Test the evaluation design with a participant without knowledge about your topic** This helps to find errors in the evaluation and harden the procedure. Changing the procedure within a big evaluation can break collected results.

17. **Simulating hard surfaces** To simulate hard surfaces by increasing the pressure is possible, if the form of the basis sole stays in the normal form and doesn't bubble up or deform significantly. Stiffeners are necessary to prevent this deformation.

18. **Simulating soft surfaces** Simulating soft surfaces by decreasing the pressure is possible, if the sole deforms by releasing the air slowly. This effect can be improved with two connected chambers, that contain a slightly constrained connection path.

5.2 Comparison

The findings in this paper are identical with findings in other, previously mentioned papers or expanding on them. In detail, this prototype has proven some key findings and therefore proved the robustness of "mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles" [51] and "CapSoles: who is walking on what kind of floor? "[50]. While this thesis did not prove robustness in all focus points of those papers, it did prove robustness in key facts like longer stance times with vibration or recognising soft undergrounds with unstable measurements. The terrain simulation from "Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study"[85] was extended by this prototype and an evaluation of five more terrains and two other changeable parameters, the cushioning and vibration.

5.2.1 Recommendations & guidelines

Guidelines for findings from the experiment are:

- Connect chambers to generate soft terrains, the Air will shift around and this generates fleeting resistance.
- The pressure have to be adjusted to the weight of the participant. Lightweight persons cant generate the same pressure as others.
- Slight vibrations can generate a soft feeling and strong vibrations feel unrealistic.

5.3 Limitations & Challenges

Every evaluation and prototype has some downsides, these have to be mentioned. Through learning from these mistakes, other researchers will not have to go through them again.

5.3.1 Prototype

The prototype is fully functional for all evaluations, but missing an on/off switch, like mentioned in 3.6.4. This would be helpful for using the prototype and missing them was a big design flaw.
A great expansion would be a pump or compressor, so that deflation can be performed with every step, not needed to be recharged manually by the user. Furthermore, the chamber system can be improved with silicon chambers, which would be more airtight, like in the reference study[84]. FDM 3D-printing has layer lines and small gaps and therefore is not ideal for air or water tight systems, resin printing or other molding methods could be explored. The use of one chamber to generate the pressure in the other was a problem, when both chambers should be used. A small chamber to generate the pressure and the two big chambers to regulate cushioning would be a better solution.

More chambers can be implemented to simulate obstacles[84] or change the foot tilt[66].
The mounting to the shoe could be improved, generating more stable measurements, but for this to work the power switch has to be more accessible. The battery has to have a better physical protection and the stiffness of the shoe has to be optimized, to flex at the points a normal shoe does and not at the PCB part. The mechanisms worked sufficient, but could be minimized. The prototype can't measure the battery charge, this could easily be fixed with a voltage divider. The battery has to be removed for charging, inductive charging would improve the design.
The sealing between the components has to be more flexible for a robuster design. The vibration motors have tiny wires, that can break fast when they vibrate. The wire part would have to be reinforced. The web server could be more improved through showing live data and giving options for analysis on the start page.
The software has some bugs. For example, to circumvent the slow internet connection and prevent upload crashes, a SD back-up would be the best option. With a live dashboard as interface the current state can be shown and errors in tests prevented.

5.3.2 Evaluation

The first two evaluations came to the same conclusion as similar studies and are therefore successful. A larger scale of participants and a well designed machine learning approach to detect changes and classify the terrains could improve the quality of the evaluation results. To proof the real robustness of the other papers, all findings have to be reproduced, not only one or two points. The evaluation with a more similar prototype can harden these findings even more.
The last evaluation can be improved with a larger participant size and some software tweaks to make the simulation more realistic, for example by changing and testing different vibration strength and pressure values. The VR support can be improved with a connected Game Engine. An AR/VR-CAVE or AR-Display can be used to generate the new underground on the given floor. The movement then isn't a fixed path and the user could walk more freely. A VR-CAVE generates

much better results in evaluations[9].
The comparing questions with value between 0 and 10, without knowing all compared terrains lead to an unwanted user behavior in starting reserved. The assignment from numbers to feelings was also difficult for some participants and they switched the directions. A scale with words may be better for intuitive answers. In this scale a free answer can represent the best results, but may not be suitable for a graphical visualisation.
To compare the simulated terrains a direct comparison with the prototype on the underground can give qualitative better results. This evaluation represents more the intuitive realism, than comparable results.
Like mentioned in subsubsection 4.4.0.7 some of the questions can't be used to gather more knowledge, because of the batch size or how the question is asked. These questions could have better been left out.

6 CONCLUSIONS AND OUTLOOK

The goal of this thesis was to build a smart footwear prototype in a normal form factor, that can change the cushioning and simulate different terrains. This goal was fulfilled successfully. With this prototype it was possible to validate findings from other researchers and extend them, as well as simulating soft terrains while walking on hard terrain.

6.1 Hardware Conclusion

While the design process the prototype was splitted in three main prototypes. The first one explores the shape of the shoe and space for the sensor system, the second one contains a pneumatic valve system with pressure chambers, to change the damping and the last one contains the vibration mechanism. After many iterations the three designs ware combined to one prototype. The prototype is not a finished product, a missing on/off switch is the biggest design flaw. Other than that, the requirements are all met and the evaluations were done successfully. The 3D model and PCB design and software can be seen on github[1] and a list of guidelines for future trials is given in subsection 3.6.5. The prototype can be rebuilt with this information.

[1] https://github.com/susesKaninchen/SimulatingShoe

6.2 Evaluation Conclusion

The first evaluation has reconstructed some findings from ”CapSoles: who is walking on what kind of floor? ”[50], that soft undergrounds produce more unstable sensor readings.
The second evaluation has reconstructed some findings from ”mobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles” [51], that the stance time will increase with vibration.
The last evaluation has extended ”Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study”[85] with terrain simulation by vibration and air pressure. The simulated terrains on linoleum are sand, grass, gravel and asphalt. Soft underground are significant realistic over hard terrains.
The findings can be used to build new VR/AR output and input devices.

6.3 Outlook

Based on this some new research in products and evaluations are possible, for example:

- Gaming accessories, they can interact with the feet or recognise feet gestures.
- Medical shoes, they can alter the gait and provide feedback to the user.
- Sports wear, tracking running information.
- Digital twin, recreate more of the human in a digital twin.
- Disease recognition, studies to recognize diseases with the gait or foot movement

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