Personalisation of safety shoe inlay soles using dynamic foot data

Integrated product design master's graduation project of
Abhijith Souparnika
in the faculty of **Industrial Design Engineering, TU Delft**
Supervised by
Dr. Toon Huysmans, Dr. Jun Wu and **Christiaan Versteegh**

TU Delft

BATA INDUSTRIALS
THE SAFETY SHOE

NEXT UPPS

Colophon

Author: **Abhijith Souparnika**
Student No. 5484057
Integrated Product Design

Chair: **Dr. Toon Huysmans**
Digital Human Modelling
Department of Human-Centered Design

Mentor: **Dr. Jun Wu**
Computational Design and Fabrication
Sustainable Design Engineering

Company Mentor: **Christiaan Versteegh**
Bata Industrials
Best, The Netherlands

University: **Delft University of Technology**
Faculty of Industrial Design Engineering
Landbergstraat 15
2628CE Delft
The Netherlands

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Abstract

This thesis project was carried out as a part of Ultrapersonalised Products & Services (nextUPPS.nl) as a collaboration between TU Delft and Bata Industrials B.V. To integrate new technologies of Industry 4.0 to enhance product and user experience, Bata Industrials, with a facility in Best, Netherlands, partnered with nextUPPS. An opportunity was identified to implement mass personalization of inlay soles by leveraging emerging technologies such as 3D scanning and 3D printing.

During this project, extensive literature research was conducted into the biomechanics of feet, the factors influencing the design of inlay soles and shoes, and advancements in 3D printing. State-of-the-art technologies and methodologies for personalized footwear, with a focus on orthotics, were also explored. Insights were gathered from experts in orthotics and inlay sole manufacturing. Additionally, data regarding dynamic plantar pressure during various activities and 3D scanning under different loads and postures were collected for subsequent analysis. Observations were made on this data to understand foot behavior, which helped filter relevant parameters for inlay sole development. Based on the research findings, a comprehensive list of requirements was formulated, encompassing all the gathered data that the inlay sole needed to adhere to.

Fused Deposition Modeling (FDM) 3D printing of Thermoplastic polyurethane (TPU) was identified as a viable and cost-effective approach for manufacturing inlay soles. To investigate this, experiments were conducted involving the mechanical testing of samples with different lattice sizes and various TPU variants, aiming to optimize 3D printing materials and parameters. The potential for multi-material printing was also explored during these experiments.

Using the insights gleaned from these efforts, a 3D-printable inlay sole was meticulously designed. Its internal structure featured a field-driven variable gyroid lattice pattern, informed by peak pressure pedobarographic data collected during walking. The shape of the inlay sole was derived from 3D scans of the user's feet. Multiple iterations were undertaken, incorporating user feedback, prototyping, and expert interviews to refine its design.

A prototype shell shoe was created specifically to evaluate the performance of the newly developed inlay sole with users. Pressure measurements and interviews were conducted comparing the new design to the conventional one. The test results confirm the design's effectiveness and underscore the importance of personalization in the inlay sole.

The conclusive insole design, along with the corresponding workflow, as well as recommendations for forthcoming actions, equips Bata to potentially launch and market the production of personalized inlay soles for their safety shoes in the future.

Introduction

Individuals' feet exhibit a wide array of shapes and sizes, and they demonstrate distinct dynamic behaviors in various circumstances. Despite the considerable variability in parameters among individuals, the customization of shoes seldom accommodates this diversity comprehensively. The morphology and pressure distribution of the foot exhibit dynamic fluctuations in response to diverse loading scenarios and activities. Consequently, both shoes and inlay soles necessitate designs that effectively address these.

In numerous industries, workers are obligated to wear safety shoes, wearing them for eight hours a day, five days a week. Prolonged standing, walking on unyielding surfaces, and ill-fitting shoes constitute the primary culprits behind foot issues among safety shoe wearers (Ochsmann et al., 2016). Research indicates that the attributes of safety shoes can modify walking patterns and the way pressure is distributed across the plantar surface. Wearing safety shoes lacking ergonomic features leads to increased trunk inclination angles and hip flexion angles, possibly resulting in negative health consequences for healthy employees (Ochsmann et al., 2016).

Critical to a shoe's comfort and ergonomic design is the inlay sole, also referred to as an insole in many sources. The inlay sole facilitates contact between the foot and the shoe, exerting substantial influence. An anatomically designed insole should be engineered to diminish plantar pressure and ensure an even distribution among support points. This approach serves to alleviate the stress encountered by these points during physical activities or extended periods of standing (Davia-Aracii et al., 2018). This becomes even more pivotal for individuals with medical conditions. For instance, the effective reduction and uniform distribution of plantar pressure significantly alleviate symptoms related to diabetic foot (Ma et al., 2019). However, it's important to note that the project's scope doesn't encompass the development of a medical device; rather, its focus is on enhancing the comfort of healthy feet.

Considering the inherent diversity of individual feet, crafting a one-size-fits-all solution is implausible, making personalized solutions indispensable to achieve uniform pressure distribution.

Design opportunity

The rising popularity of 3D printing as a workable production method introduces opportunities for mass customization. Traditional techniques such as molding and machining are limited to crafting insoles with homogeneous mechanical properties (Ma et al., 2019). On the other hand, 3D printing empowers us to adjust the internal structure of components in ways that were not achievable using conventional manufacturing methods. By integrating 3D scanning, dynamic pressure mapping, and 3D printing into safety shoe inlay soles, we can create highly personalized support and cushioning profiles by modifying the shape, fit, and internal structure of the inlay soles. Moreover, 3D printing is economically feasible, as demonstrated by the calculations of Davia-Aracil et al. (2018), which showcase significant reductions in material, equipment, and operator costs, albeit with a minor increase in production time.

The aim of the project is to develop a design workflow to use the data collected from 3D scans of feet, and dynamic pressure mapping, to create a personalized inlay sole (footbed) that can be inserted into safety shoes that provides better comfort and fit to the user.

Most commercially available inlay soles tend to be thin in order to ensure compatibility with standard shoes. Unfortunately, this thinness limits the extent of customization that can be applied. The proposed inlay sole, however, will serve as a replacement for both the existing inlay sole and the midsole of a conventional safety shoe. This substitution grants a greater volume for incorporating personalization, offering enhanced control over localized cushioning properties and contour support, particularly in the forefoot region. These capabilities surpass what is attainable with typical inlay soles currently accessible on the market.

Given that this project delves into the utilization of information to derive shape and stiffness specifications while also investigating the feasibility of producing them via 3D printing, Bata will be in a position to employ this as a foundational framework for implementing mass personalization in the future.

Design Approach

The design approach employed in this project is depicted as a modified double diamond structure, as illustrated in Figure 1. The report is organized into sections corresponding to this approach.

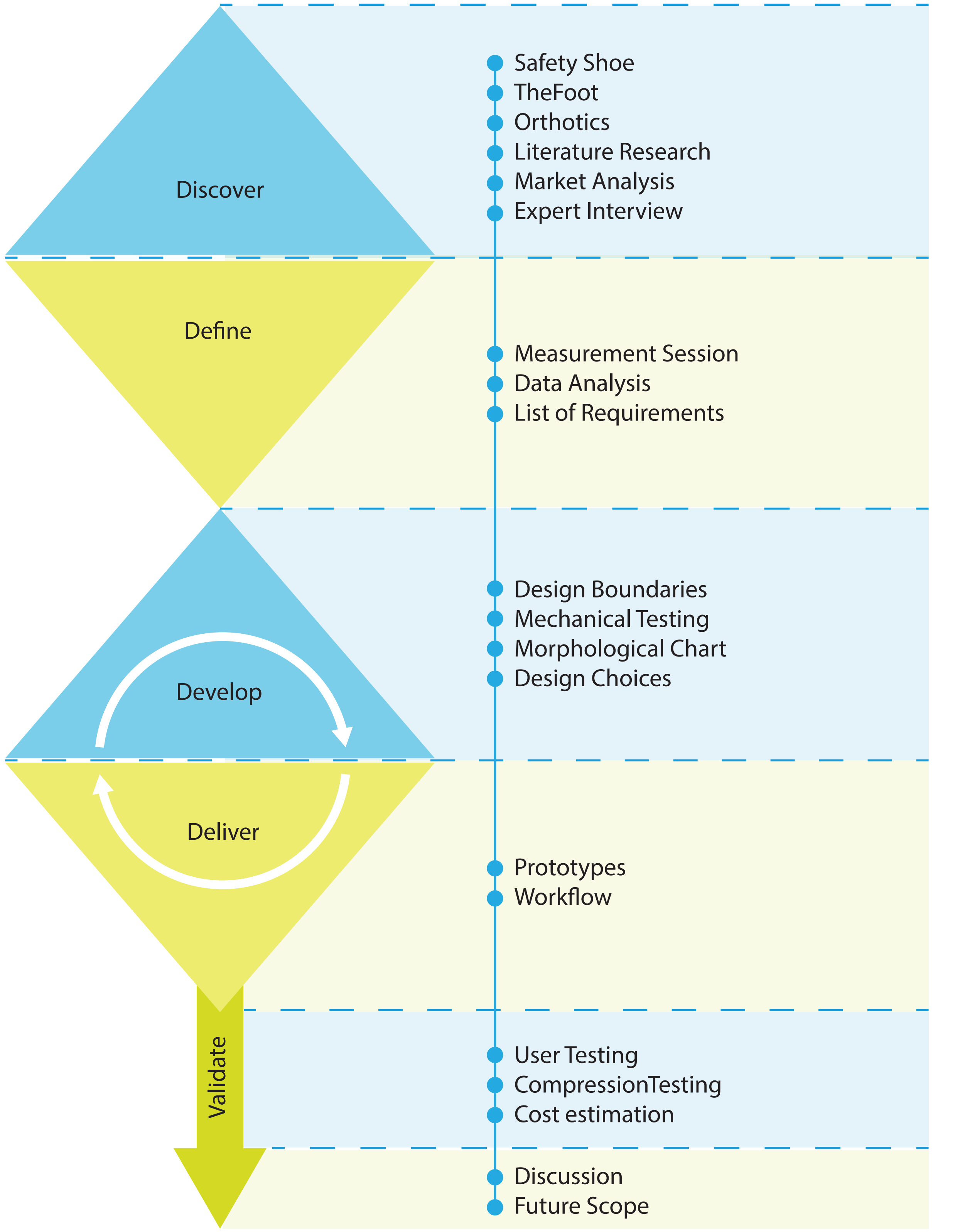


Figure 1. Design Approach

1. Discover

The Discover stage involves comprehensive research into the subjects pertinent to the project. This entails field visits, perusing scientific journals, conducting market research, interviewing experts, and conducting desktop research.

1.1. Safety Shoe

In this chapter, different regulations and standards used in safety shoes, its components, functionalities and manufacturing are investigated to better understand the context.

Safety Footwear Standards

The safety footwear produced throughout Europe follow the EN ISO 20345. This norm has the following classifications:

- SB: Safety shoes with toecaps, can withstand an impact up to 200 Joules and compression of 15kN. SB shoes also satisfy a whole list of criteria, including many different quality standards for shaft and sole, comfort requirements, minimum slip resistance and oil resistance.
- S1: SB plus anti-static properties, and energy-absorbing and closed heel.
- S1P: S1 plus perforation-resistant mid-sole.
- S2: S1 plus upper with a certain maximum water permeability and water absorption.
- S3: S2 plus perforation-resistant mid-sole and outsole with a certain quantity of tread

The naming convention is used to specify other features that may be present in the footwear:

- P. Puncture resistance: the footwear incorporates insoles (which may be metal or textile anti-puncture) with a puncture resistance of 1,100N force.
- C. Conductive footwear: its electrical resistance is from 0 to 100 kilohms. It is designed to evaporate electrostatic charges.
- A. Antistatic footwear: Although it is similar to label C, this label is intended for safety footwear designed to dissipate electrostatic charges between 100 and 1,000 kilohms.
- HI. Heat resistance of sole: insulation against heat of the sole of the footwear up to 150°C.
- CI. Cold resistance: provides insulation against cold of the sole of the footwear up to -17°C.
- E. Energy absorption in the heel area: this area of the safety shoe must be able to absorb a minimum of 20J of energy.
- M. Metatarsal protection: the footwear incorporates additional metatarsal safety.
- AN. Ankle protection: the footwear incorporates added ankle protection.
- CR. Cut Resistance: the shoe has a protection zone resistant to possible zones
- WR. Waterproofing: the entire shoe must be waterproof.
- WRU. Resistance to water penetration and absorption: the upper of the shoe shows resistance to water inclusion and absorption.
- HRO. resistance to contact heat: the sole can withstand contact heat with temperatures up to 300°C.
- FO. Resistance to hydrocarbons: the sole of the footwear is resistant to contact with hydrocarbons.

Figure 2. Illustration showing features of safety shoes (GPI, 2023)

Components of Safety Shoe

- **Upper**: The upper is the part of the shoe that covers the foot and is usually made of leather, synthetic materials, or a combination of both. It provides overall support, durability, and protection from impacts, abrasions, and chemical spills.
- **Safety Toe Cap**: The toe cap, often made of steel, composite materials, or aluminium, is located at the front of the shoe, and protects the toes from heavy objects, compression, or impacts. It prevents injuries such as crushing or stubbing.
- **Lining**: The lining is the inner material that comes in contact with the top of the user's foot. It enhances comfort, absorbs moisture, and helps regulate temperature to keep the feet dry and comfortable throughout the workday.
- **Inlay sole**: This is the part of the shoe that comes in contact with the bottom of the user's foot (or socks), and provides climate regulation, cushioning, and comfort for the wearer. This is generally made of low-density PU foam or EVA.
- **Insole**: This is the bottom layer of the upper made of polyester. This defines the boundary of the midsole. This could also provide anti-penetration. And could also have a metal plate pasted onto it.
- **Midsole**: The midsole is a layer of material, typically made of medium-density PU foam sandwiched between the outsole and insole. It provides shock absorption, cushioning, and helps in providing stability.
- **Shank**: Shank in an insert made of TPU placed inside the midsole which provides anti-torsion, midfoot stability, Shock absorption and prevents core incineration.
- **Outsole**: The outsole is the bottom part of the shoe that contacts the ground. It is usually made of PU to provide traction and prevent slips, trips, and falls. The outsole may also have additional features like abrasion resistance, oil resistance, heat resistance, or electrical resistance.

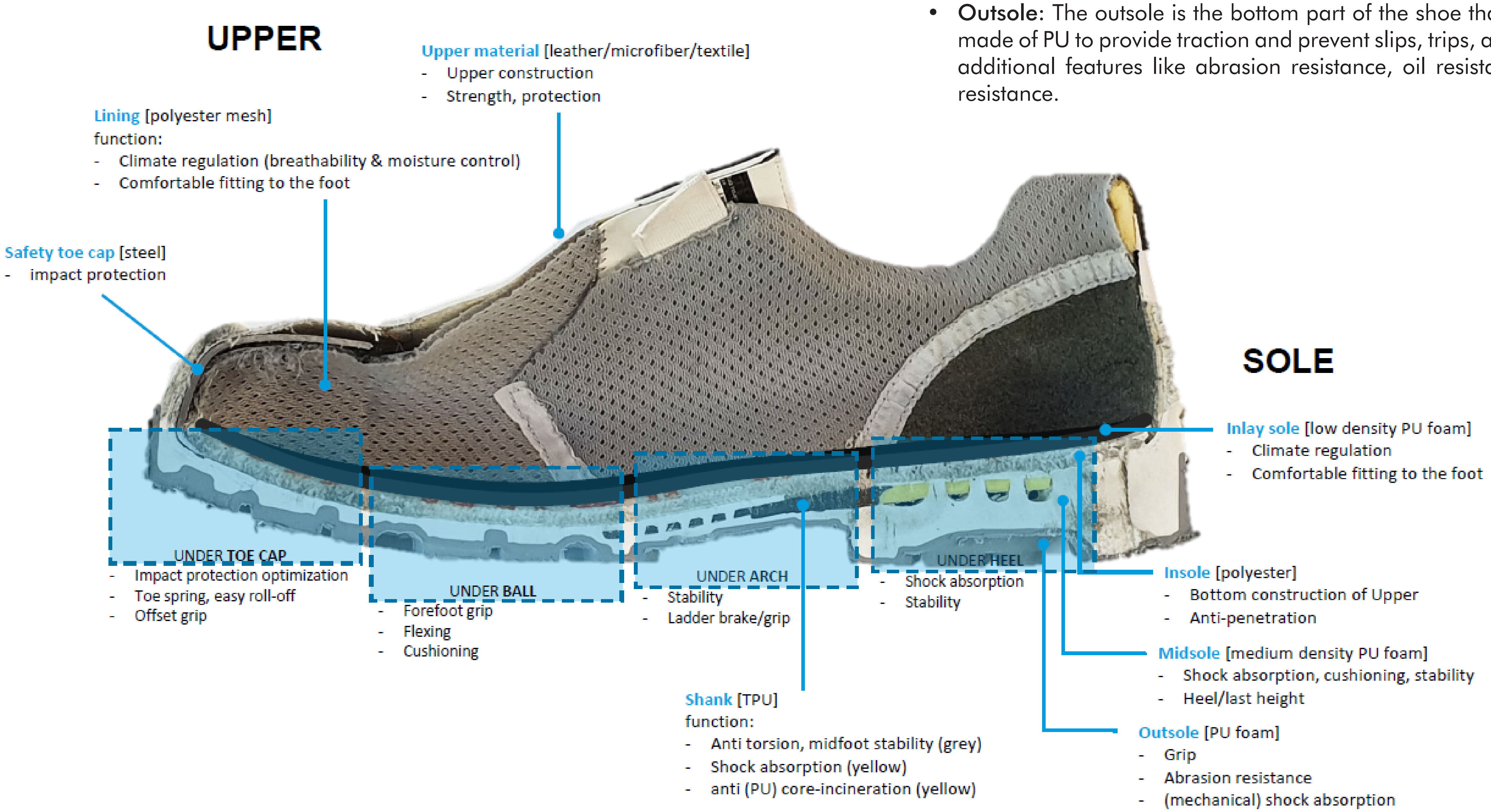


Figure 3. Cross section of a safety shoe with the components and their functions.

The bottom of the shoe can be divided into zones with unique functions:

- **Under heel:** The heel is the first part of the foot that comes in contact while walking and takes the most impact and so this area of the Sole provides shock absorption and stability.
- **Under arch:** This area provides a ladder grip and helps stabilize the foot.
- **Under Ball:** The treadline (the line at which the foot bends) falls in this area. So, this area is designed to flex. The ball of the foot also experiences high pressures, and this area provides cushioning and also grip for the forefoot.
- **Under toe cap:** This area is bent to provide a toe spring and easy roll-off during walking.

Shoe Assembly

To understand the safety shoe manufacturing process, the Bata production plant in Best was visited.

Last:
The Shoe Last holds utmost significance in determining the form and functionality of any shoe. It essentially dictates the shape, fit, performance, ergonomics, and style of the shoe. The entire construction process of the shoe revolves around this foundational element. The last represents a mechanical replica of a foot (including the inlay sole). The fundamental aspects of a last and its constituents are depicted in Figure 4. A common plastic last used in production is illustrated in Figure 5.

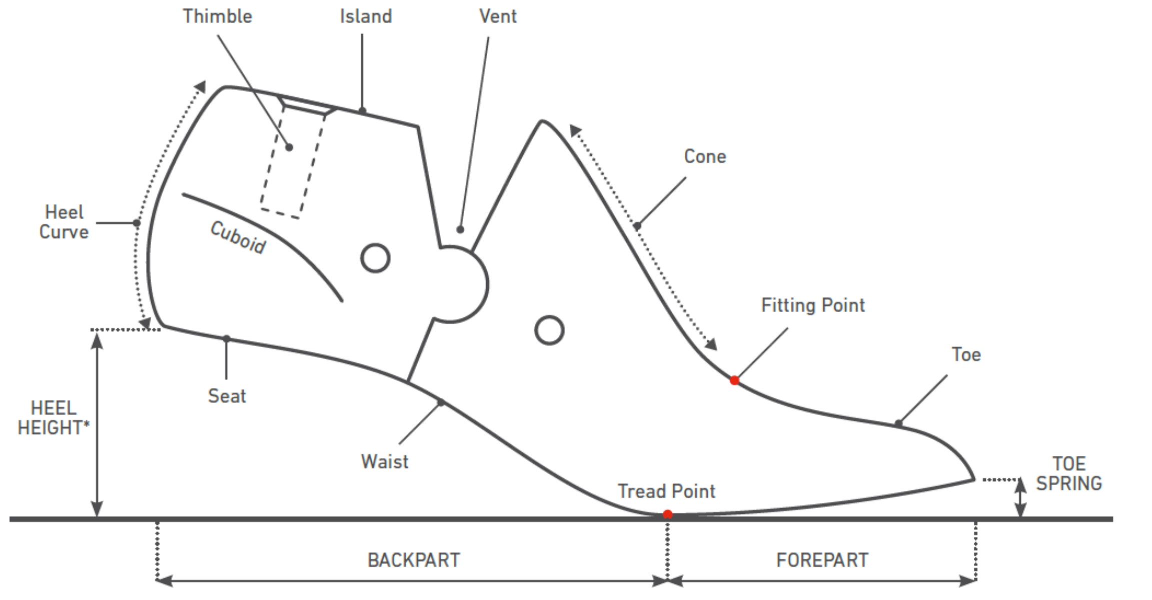


Figure 4. Basic shoe last (Bata Shoe last Manual, 2016)

Figure 5. Plastic Last (Bata Shoe last Manual, 2016)

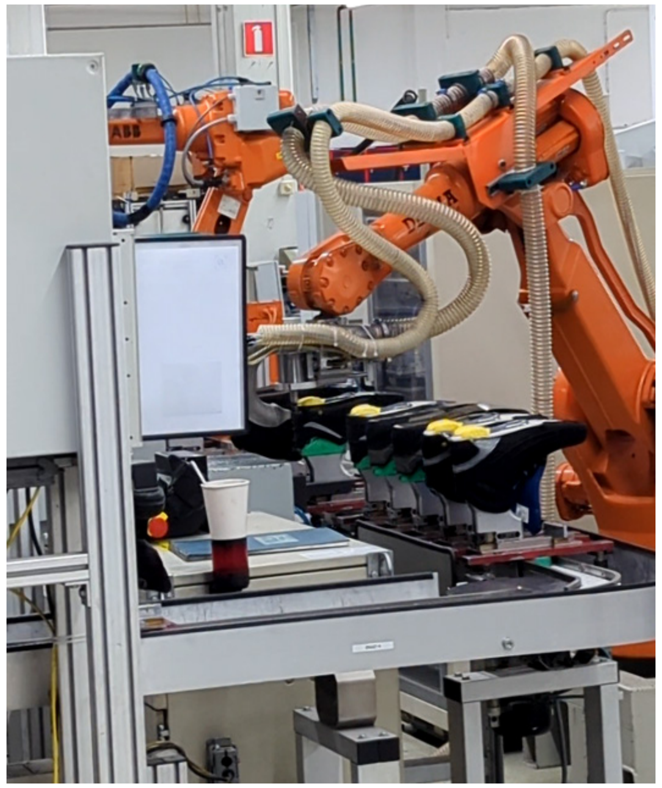


Figure 6. Automated placement of shank

Figure 7. Injection Moulding of sole

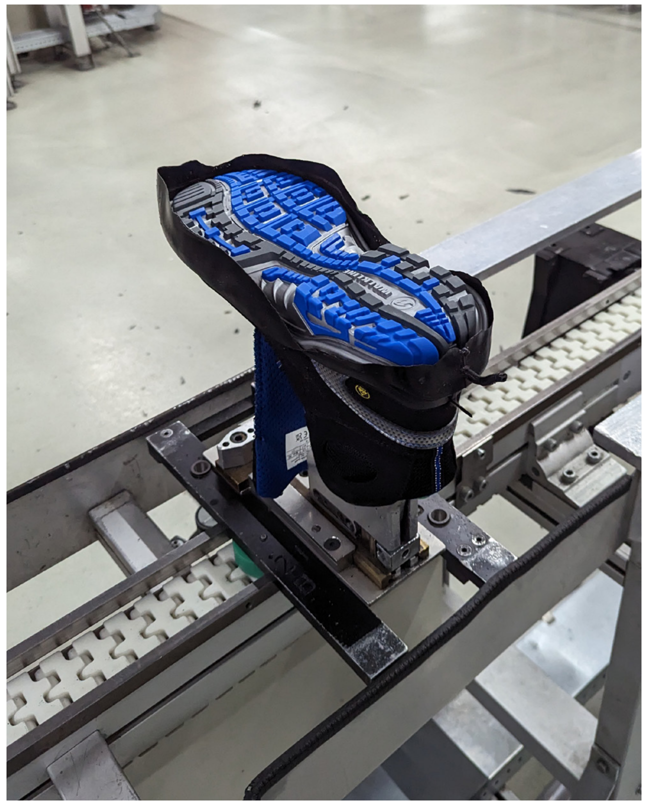


Figure 8. Shoe with injection moulded midsole

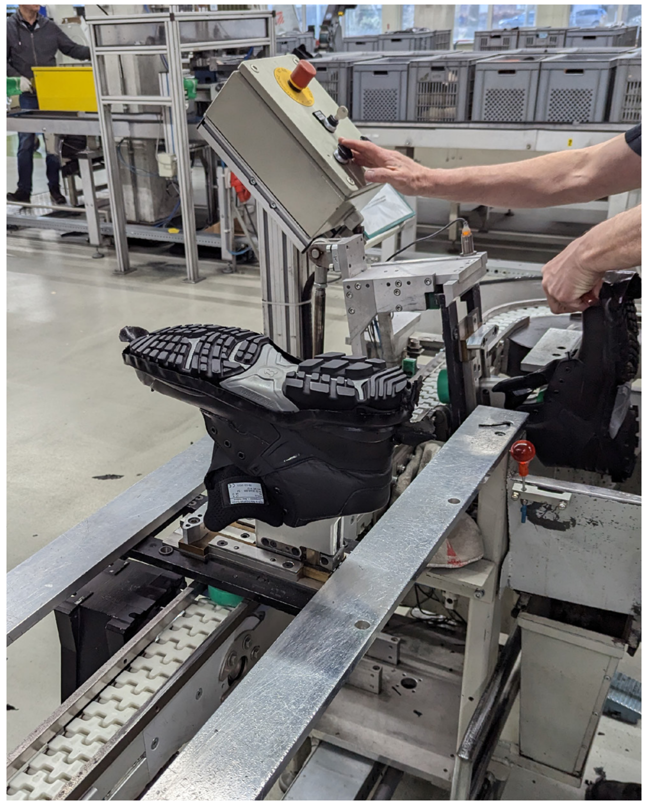


Figure 9. Trimming manually

Production process:

The lasts are introduced to the assembly line, and the uppers with toe caps and insoles are affixed onto them. Sanding operations are performed on the uppers to enhance the adhesion of the sole. Subsequently, a shank, and optionally, a steel plate, are attached to the insole using glue (refer to Figure 6). Following this step, the shoe proceeds to an injection molding machine (refer to Figure 7). At this stage, either a pre-made outsole is utilized and the midsole is injection molded, or a two-stage injection molding process is employed to create both the outsole and midsole. Some automated trimming of excess material takes place (refer to Figure 8), and the final refinements are carried out manually (refer to Figure 9). Ultimately, the inlay sole is inserted into the shoe and the product is prepared for packaging. A visual representation of the production process can be found in Figure 10.

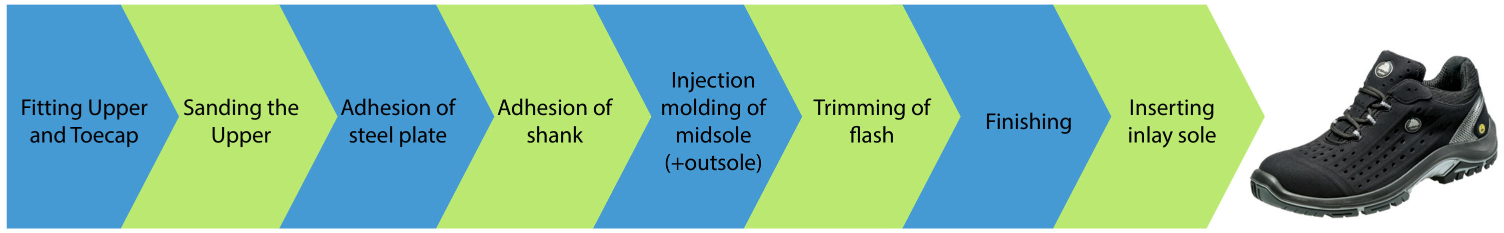


Figure 10. Production Process

Conclusion:

Examining regulations reveals that since the inlay soles are intended for use in safety shoes, they must also adhere to several requirements, including electrostatic discharge, energy absorption, heat and cold resistance, and slip resistance within the shoe.

Given that the newly designed inlay sole replaces the midsole, inlay sole, and shank, it must undertake the functions of these components, such as shock absorption, cushioning, stability, anti-torsion properties, climate regulation, and ensuring a comfortable fit for the foot.

The personalized inlay sole could be offered alongside the shoe as part of the production line or as a separate product. In both cases, compatibility with different shoe styles and easy, snug insertion are vital considerations.

1.2. The Foot

Understanding the fundamental anatomy of the foot is crucial to understand the inner workings of the shoe. A shoe has to cover the foot and mimic its movements with significantly fewer moving components than a human foot, which has more than 100 separate moving parts. The health of the rest of the body is also directly related to the foot. To design an inlay sole, it is important to know the anatomy of the foot.

Different types of foot

Since the shape of the foot of each person can vary a large amount, broad classifications have been made to differentiate them. The different types of foot based on the structure of the toes as well as the arch are illustrated in Figure 11.

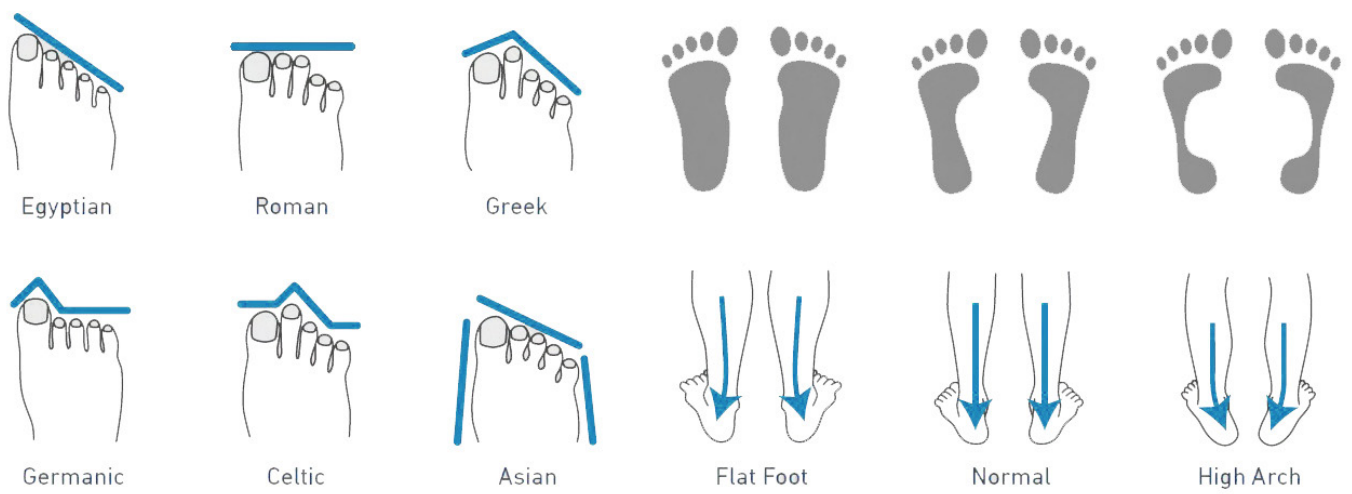


Figure 11. Different types of feet (Bata Shoe last Manual, 2016)

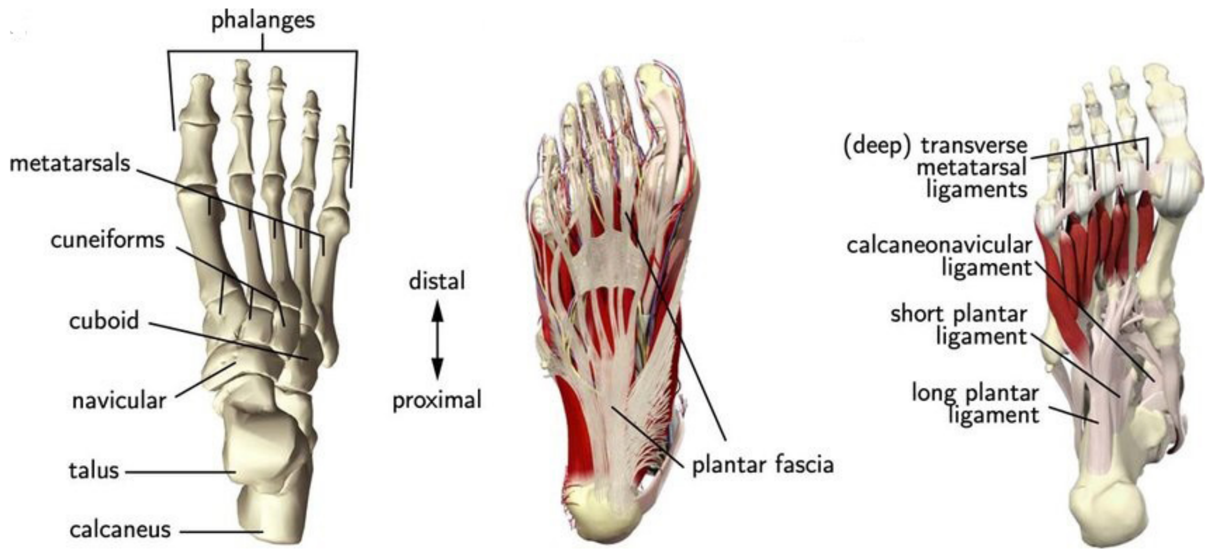
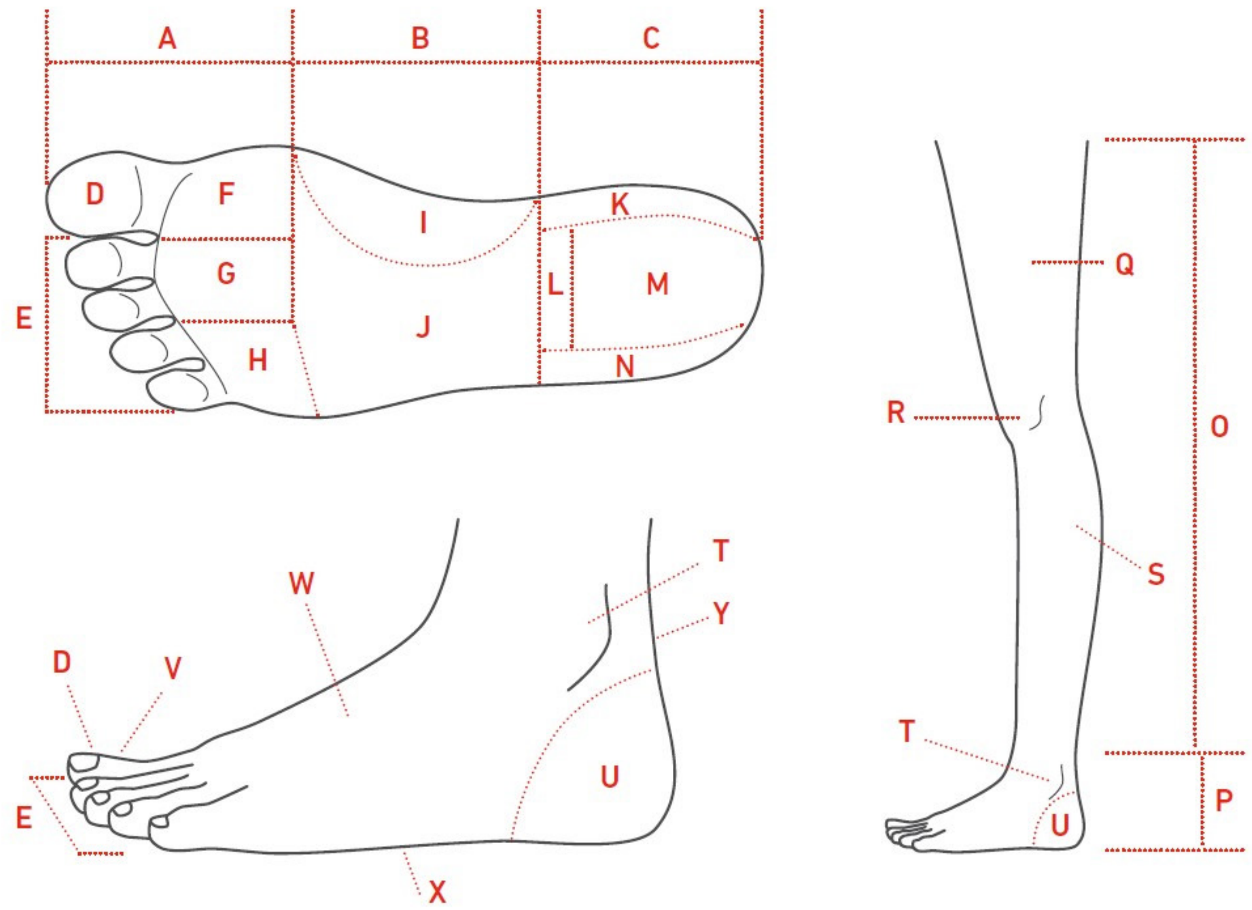


Figure 12. Major bones and ligaments of the foot (Venkadesan et al., 2020)

Anatomy of the foot

The important bones and ligaments present in the foot are illustrated in Figure 12.

Based on this internal structure, the foot is divided into different segments as illustrated in Figure 13



A	Forefoot	N	Outer Heel
B	Midfoot	O	Leg
C	Heel	P	Foot
D	Nail	Q	Thigh
E	2nd, 3rd, 4th & Little Toe	R	Knee
F	1st metatarsal Head	S	Calf
G	2nd & 3rd Metatarsal Head	T	Rearfoot
H	4th & 5th Metatarsal Head	U	Heel
I	Arch	V	Hallux / Big Toe
J	Lateral Midfoot	W	Upper Side of the Foot
K	Inner Heel	X	Sole of the Foot
L	Heel Front	Y	Achilles Tendon
M	Heel		

Figure 13. Segmentation of the foot (Bata Shoe last Manual, 2016)

Biomechanics of foot:

The foot contains three axial joints, which gives it the flexibility to take any posture. In the talus region, the three primary axes of movement come converge. All of the joints are partially engaged, especially during rotational motions to adjust the foot to an uneven terrain, however the ankle joint serves as the primary joint for locomotion despite being constructed as a hinge joint. These degrees of Freedom are illustrated in Figure 14.

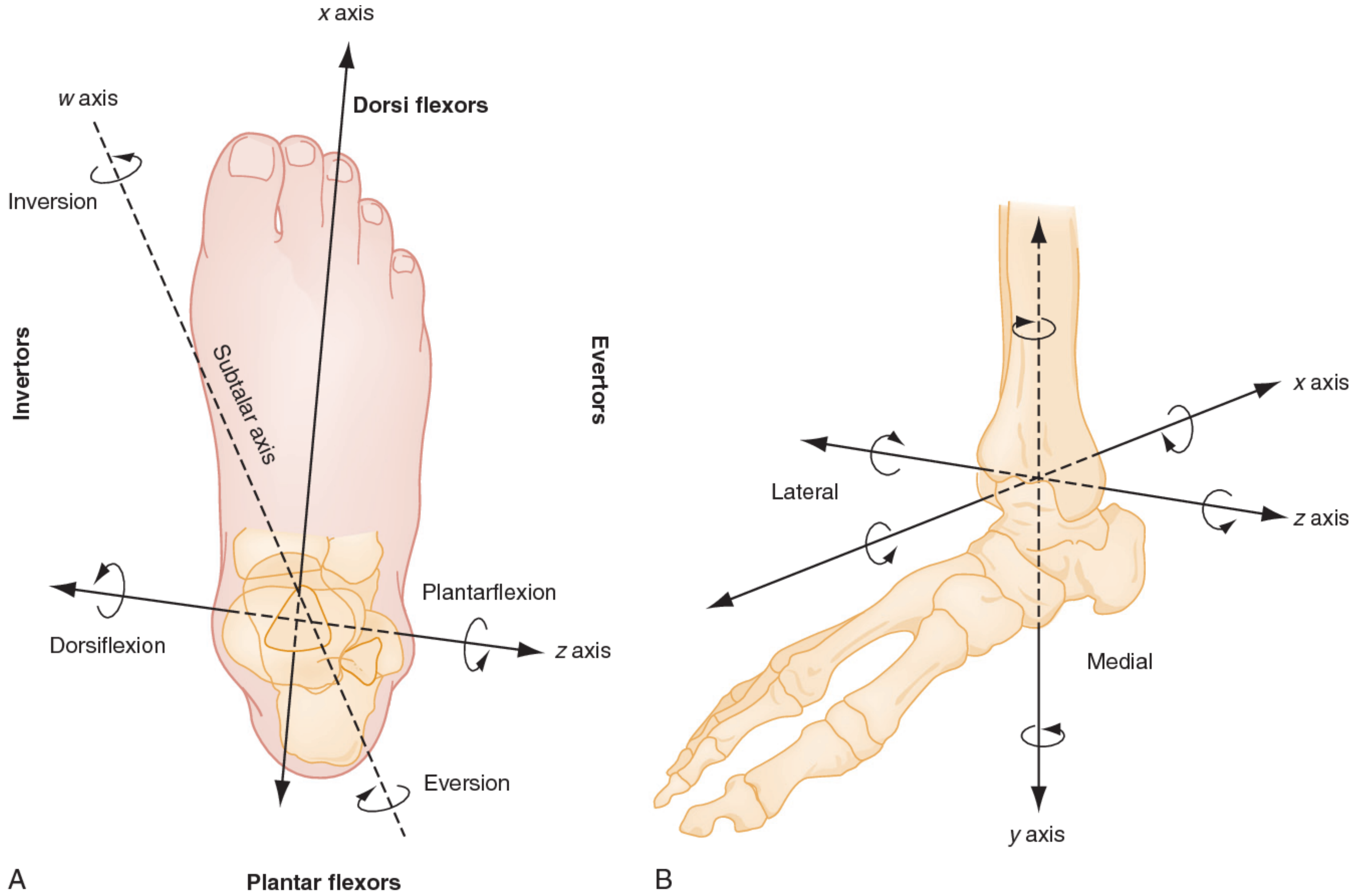


Figure 14. Degreen of Freedom of the Foot. (Phlanges, E. ,2006)

Conclusion:

This chapter helps identify the nomenclature for different areas of the foot and the function they play. The inlay sole should be designed so that it accommodates these features (ex. have flexibility near the flexible regions of the foot) and provides proper support in the appropriate sections of the foot.
Since there is a large difference in the shape of the feet of individuals, personalization features should be designed taking these differences into consideration.

1.3. Orthotics

In the context of understanding inlay soles, it's useful to know about personalized orthotics. Orthotics are personalized devices for supporting, aligning, or correcting feet, ankles, and legs. They include items like insoles, arch supports, toe pads, and braces, tailored for specific foot conditions. Custom orthotics are different from generic insoles as they're precisely customized for an individual's foot.

There are three main types of orthotics:

Rigid Orthotics: Comprising firm materials like plastic or carbon fiber, rigid orthotics are primarily intended for walking or dress shoes. They are crafted from a mold created through methods such as plaster casting or imaging the foot. (Figure 15)

Soft Orthotics: Primarily designed to absorb shock, enhance balance, and alleviate discomfort or pressure from sensitive areas, soft orthotics are constructed using soft and cushioning materials. They are worn against the foot's sole, extending from heel to the ball of the foot and encompassing the toes. (Figure 16)

Semi-Rigid Orthotics: Geared toward providing foot balance during activities like walking and sports participation, semi-rigid orthotics are tailored to different sporting requirements. They are typically composed of layers of soft materials reinforced with sturdier components. (Figure 17)

Figure 15. Rigid insole (JM Orthotics, 2023)

Figure 16. Soft insole (JM Orthotics, 2023)

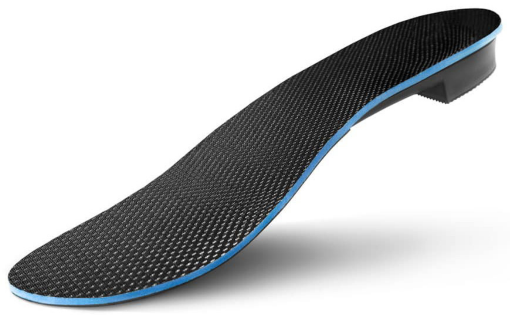


Figure 17. Semi-rigid insole (JM Orthotics, 2023)

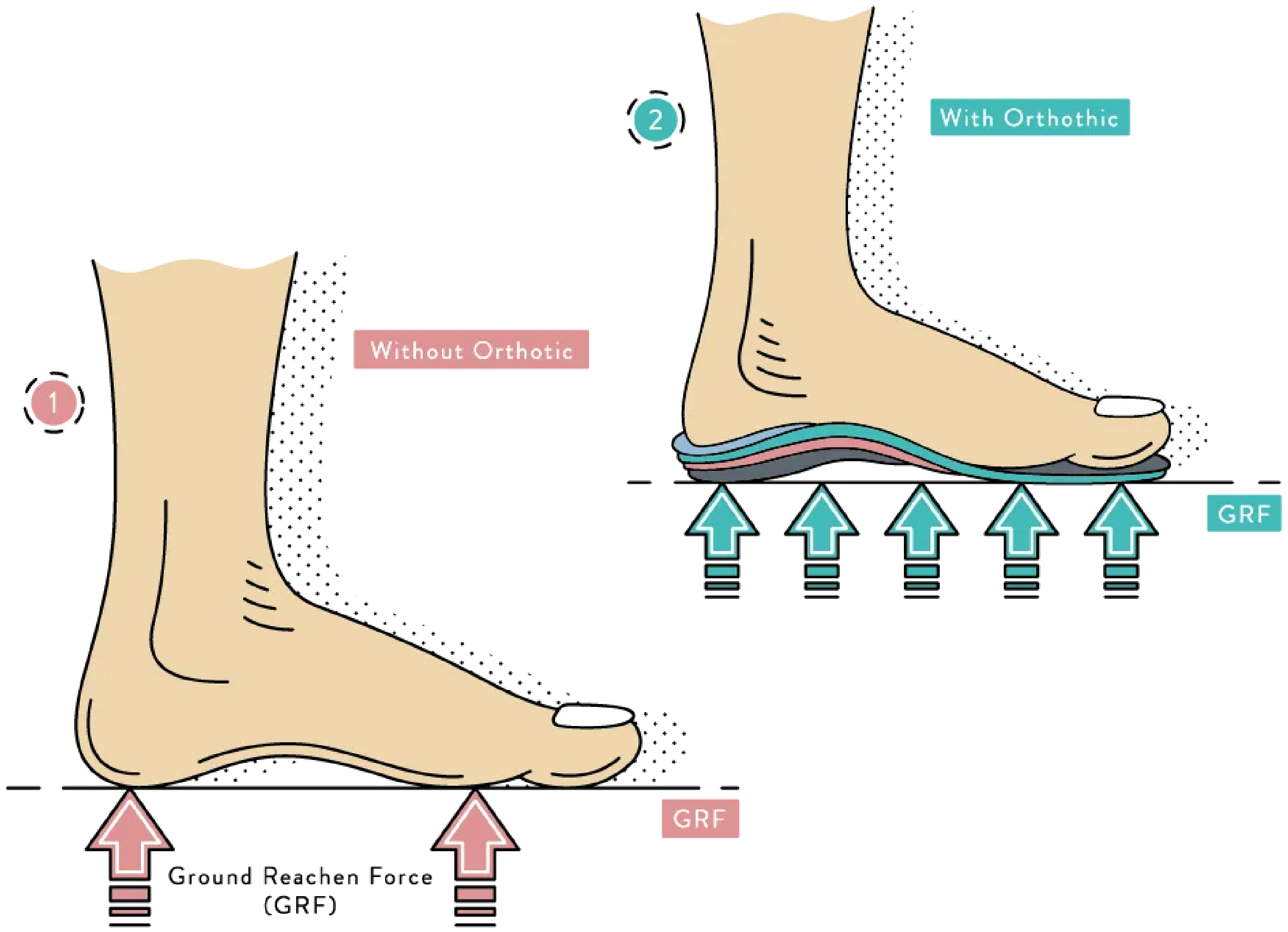


Figure 18. Effect of Orthotics(Thefoothub, 2023)

Orthotics, in general, influence the ground reaction force, which is the pressure transmitted from the ground to the foot when standing, walking, or running. By modifying these forces, the aim is to enhance foot functionality and diminish excessive forces that might lead to foot-related injuries. This is illustrated in Figure 18.

Conclusion:

As orthotics are personalized care products for the foot, exploring the design and manufacturing methods of different types of orthotics can inspire the ideation process in creating personalized inlay soles. Literature study done on the field on orthotics could provide important information useful for the project.

1.4. Literature Research

This section delves into the current state of scientific literature encompassing various domains related to this project.

Foot Measurement devices:

Abdul Razak et al., (2012) discuss and reviews different systems that are available for measuring plantar pressure. Broadly, pressure measurement systems can be classified into platform systems and in-shoe systems. Platform systems are generally restricted to research laboratories. They are easy to use but cannot ensure natural gait without familiarization with the user. (Refer Figure 19)

Figure 19. A platform-based foot plantar pressure sensor emed® by Novel (Abdul Razak et al., 2012)

In shoe systems have flexible sensors embedded in the shoe such that the measurements are taken from the interface between the foot and the shoe. This system is portable which allows a wider variety of studies with different gait tasks, footwear designs and terrains (Refer Figure 20).

Figure 20. In shoe Pressure Sensor (Abdul Razak et al., 2012)

The sensors themselves could be Capacitive, Resistive, Piezoelectric or Piezoresistive and can be wired or wireless. Literature also proposes low-cost 3D printed pressure sensing devices. A few notable examples are Ntagios, (2022) where a capacitive pressure sensing device with four sensing zones was developed that is housed in a 3D printed insole and Leal-Junior et al, (2019) which implemented a polymer optical fibre (POF) based sensing in a 3D printed TPU insole.

For gathering information about the morphology of the foot, 3D surface scanning provides the ability to obtain a digital representation of the foot quickly and easily. Telfer & Woodburn, (2010) analyze different measurement systems that are commercially available and analyse the different foot parameters captured by them. They conclude that the systems obtain accurate representations, and the increasing affordability of the design adds to its appeal. Lee et al., (2014) compare 3D scanning to conventional methods like a digital caliper, ink footprint and digital footprint and conclude that a 3D foot scanner is recommended for collecting data due to higher precision, accuracy and robustness. Farhan et al., (2021) also compare 3D scanning to using a plaster cast, foam impression box and clinical assessment for the design and production of in-shoe orthoses and conclude it to be faster, however, accuracy and reliability are variable.

Another approach to analyzing the behavior of the foot was not to perform real-life measurements but to simulate the biomechanics of the foot digitally and analyze it through FEA. Telfer et al., (2016) created a geometric accurate model of the forefoot anatomy to predict plantar pressures. Here, information about the metatarsals and soft tissues is extracted from CT scans, ultrasonic sensors and 3D scans of an unloaded foot. Pressure data was gathered and used to define the properties of the foot to behave accurately during FEA. Further, Telfer et al., (2017) also developed an optimized insole for uniform pressure distribution based on the FEA simulation of this model. (Refer Figure 21)

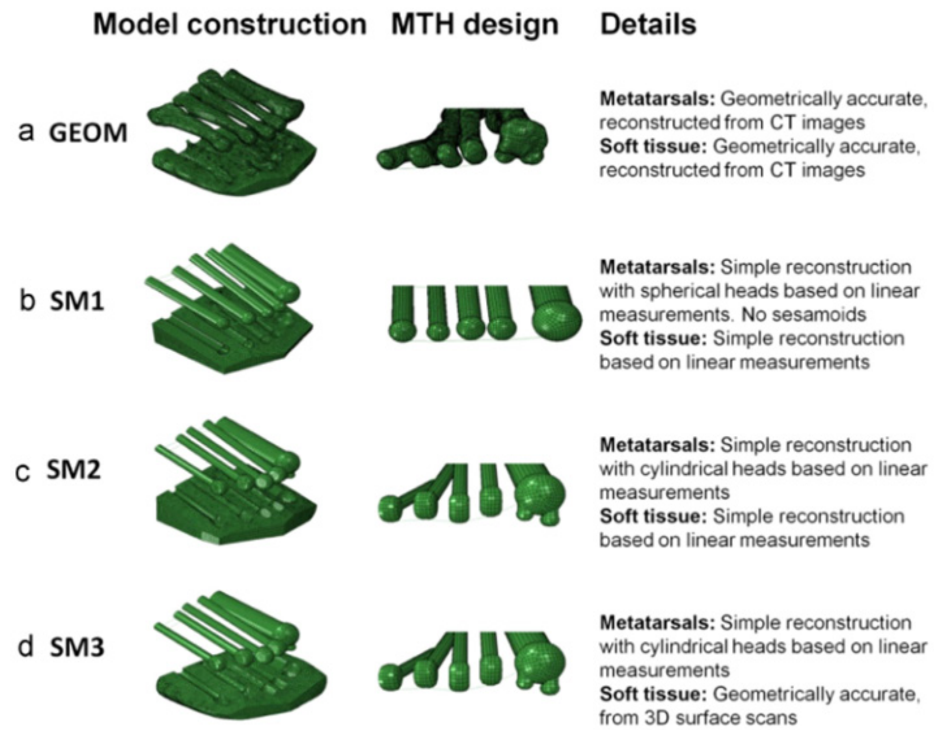


Figure 21. Digital Models of forefoot created by Telfer et al., (2016)

Orthotic foot care

The literature on orthotic foot care was used to guide the functionalities and form of the inlay sole to be designed. The bulk of the literature related to inlay soles study plantar pressure distribution and methods to relieve pressure hotspots. Plantar pressure was the most important metric that has to be taken into account while designing an inlay sole. The measurement of plantar pressure can be used to analyze unhealthiness including lower limb problems and diabetic conditions and can even help provide remedial measures.

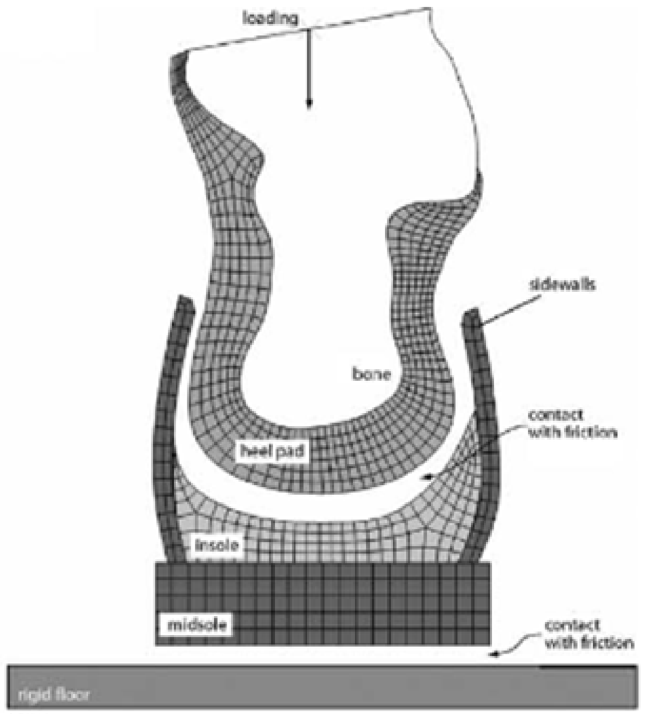


Figure 22. Plane strain finite element model of the heel (Goske et al., 2016)

Goske et al. (2006) studies the effect of 27 different insole designs on the heel using two dimensional plane finite element modelling (Refer Figure 22) . The plantar pressures predicted were validated by experimental trials. This study showed that conformity of the inlay sole was the most important design variable, while peak pressures were relatively insensitive to the material of the insole. Having an insole that conforms to the shape of the heel of the user is found to give 44% pressure relief compared to flat insoles.
Hayda et al., (1994) evaluated volunteers with normal asymptomatic feet to test the effectiveness of metatarsal pads. Different types of pads were used at different positions to evaluate their effectiveness. It was found that a small felt pad caused the greatest and most consistent decrease in pressure at the metatarsal heads. The study shows that incorporating a metatarsal pad effectively decreases plantar pressure within the shoe.

Tse et al., (2020) examines the effect of foot posture on the biomechanical responses to different designs of lateral wedge insoles with arch support. Healthy volunteers were tested on different designs of insoles. The study finds that insoles using a variable stiffness arch support with higher stiffness laterally (on the outside of the foot) and lower stiffness medially (on the inside of the foot) is superior to a uniform stiffness arch support for orthotic insoles.

Leber & Evanski (1986) compares the effectiveness of seven conventional shoe insole materials. The materials tested were: Latex foam, Plastazote, Dynafoam, Orthofelt, PPT, Spenco, and Molo. The pressures are measured using Harris and Beath footprinting technique The insoles show a decrease in mean metatarsal pressures by 23% to 53% with PPT and Plastazote giving the highest effectiveness. The Mean pressure was reduced from 398.15kPa to 186.33kPa. This data shows the expected range of pressure reduction that is expected from an insole.

Mishra (2020) compares Micro cellular rubber and silicone gel insoles using pedobarography. Here, both were found to be effective in reducing plantar pressure with MCR insole reducing pressure by 62.79% in the Hallux region.

3D Printing

As the project was aimed for mass customization, the most suitable solution was to make use of additive manufacturing (Dong et al., 2019). This also enables control of the internal structure, which is not possible with conventional manufacturing methods. Many research papers (Davia-Aracil et al.(2018) ,Ma Z (2019) propose FDM 3D printing to be a viable means of manufacturing personalized inlay soles as it is cost effective.

Sachyani Keneth et al., (2020) while discussing 3D printed soft robotics components, reviews 3D printing techniques that can produce high-performance materials. FDM printing is restricted to thermoplastic polymers, which are flexible and most commercial filaments are TPU. In polyjet printing, restrictions regarding viscosity, surface tension and evaporation rate restricts research and development. The new research on flexible and stretchable materials for 3D printing is focused on Stereolithography (SLA) and Direct Ink Writing (DIW) printing methods, in which it is easy to develop new ink compositions.

Davia-Aracil et al. (2018) identifies the potential of additive manufacturing, FDM in particular in impacting the insole industry. The paper reviews certain CAD methodologies for the production of insoles using additive manufacturing. The approach taken here is to split the bounding surfaces into 3 separate surfaces: the bottom surface, upper surface and side surface. The CAD tool reviewed is used to generate, based on user input of 2D patterns, cushion structures enclosed within the surfaces. (Refer Figure 23) The shape of the structures determines the amount of cushioning provided in each area of the insole. According to the analysis done by Davia-Aracil et al. (2018) the viability of FDM for creating insoles comes from the fact that, the TPU filament is cheaper than EVA foam and 3D printers being 8-10 times cheaper than CNC.

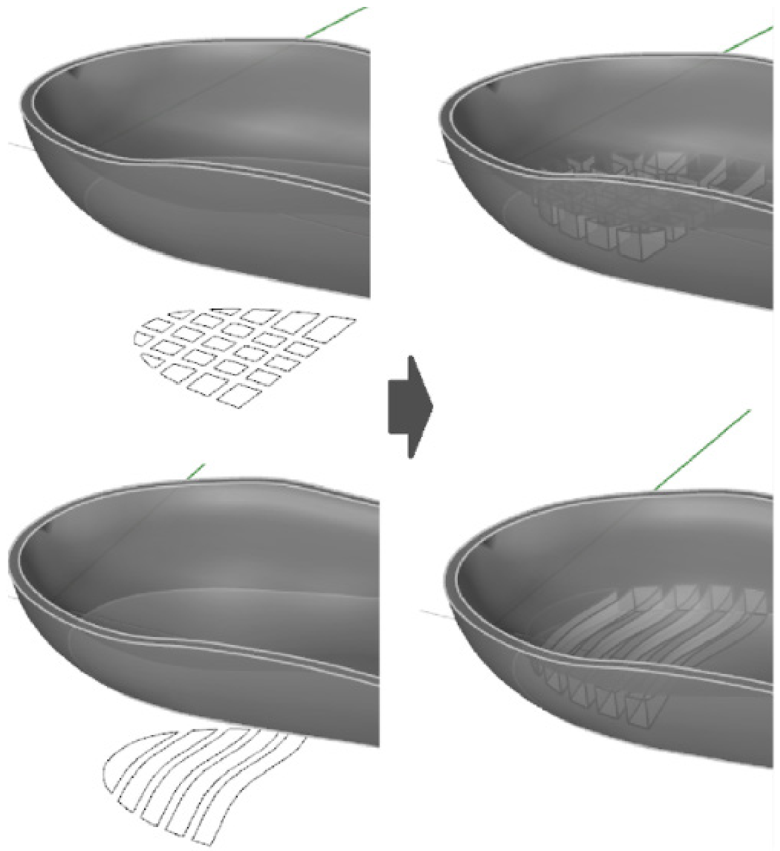


Figure 23. 2D Pattern changed to cushioning (Davia-Aracil et al., 2018)

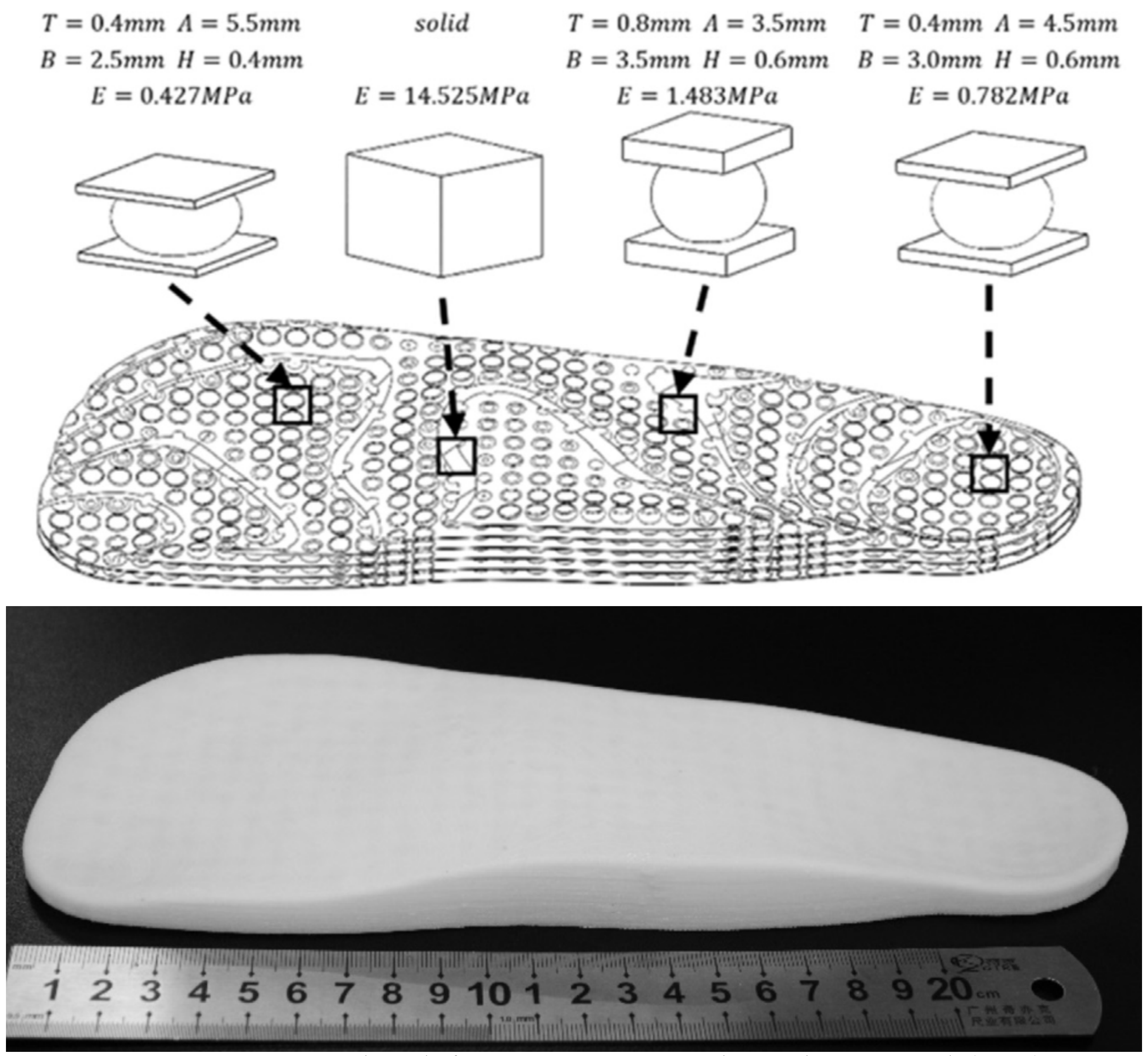


Figure 24. Customized insole from porous structures designed my Ma et al. (2019)

Ma et al. (2019) identifies the limitations of conventional manufacturing methods to only produce homogenous structures. Here a porous design was made with different parameters which was 3D printed in TPE and parameters of the structural units were varied and compressive tests were performed and FEA was done. These porous structures were incorporated into an insole design. (Refer Figure 24)
Dong et al. (2019) analyzed the mechanical response of different lattice topologies like diamond, Grid, X shape and Vintiles in shoe soles. Here conformal lattice structures are generated which fit into the curved surfaces of the sole. They perform FEA testing of the soles and further print part of the sole using FDM printing in TPU 95A and subject it to compressive testing. The experiment shows that the lattice structure is highly influential in determining the mechanical response(Refer Figure 25). They also propose the possibility of flexibly controlling

the stiffness of the sole by changing the relative densities of the lattice.

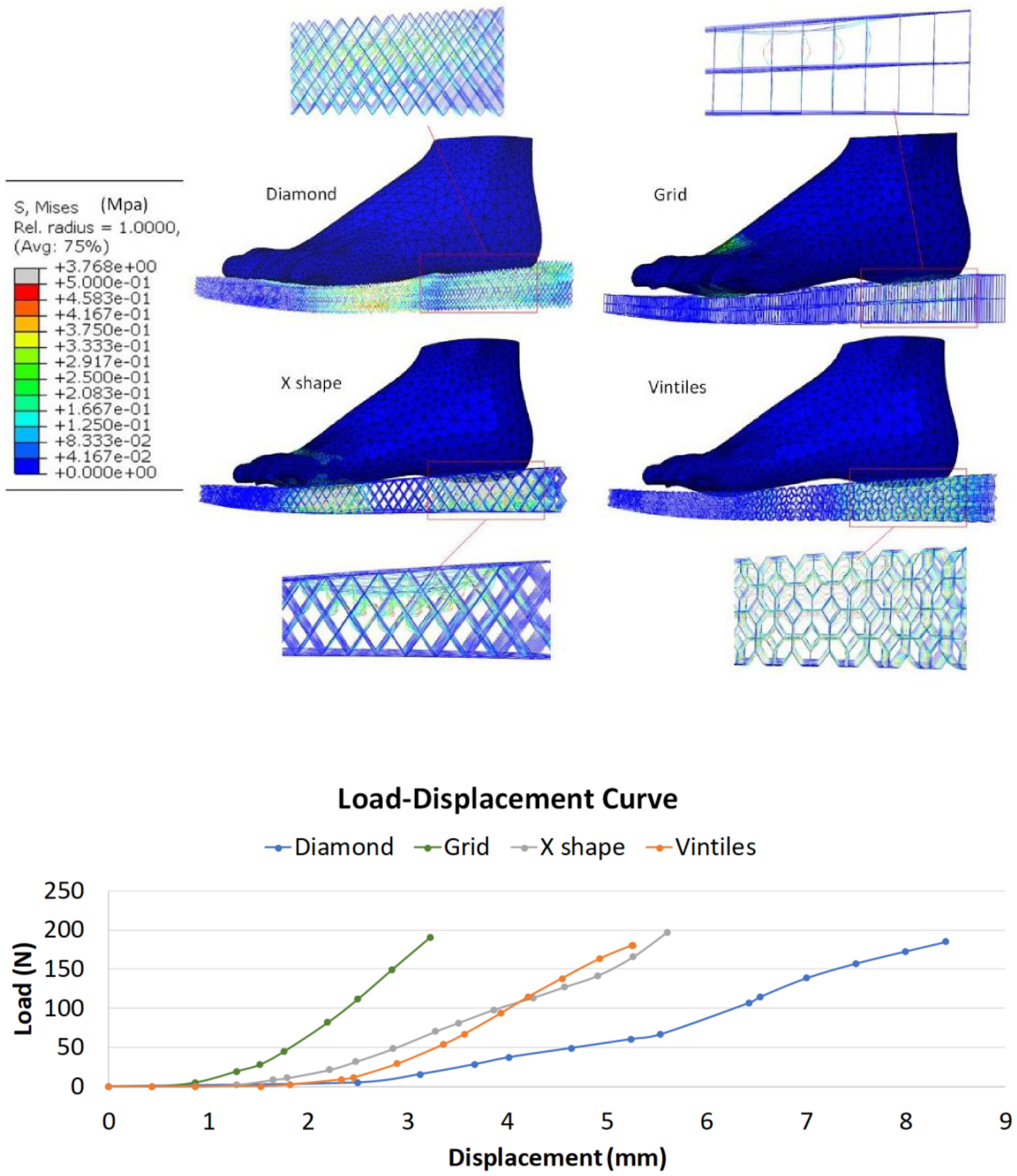


Figure 25. Mechanical response of different lattices observed by Dong et al, (2019)

Kuipers et al. (2019) identified that to produce high-quality fabrication results, extrusion based 3D printing requires not only self-supporting structres, but continuous paths free of self-overlap. In accordance, they propose a novel self-supporting space-filling surface which supports spatially graded density called crossfill that is ideal for production of functionally graded materials (FGM) using FDM (Refer Figure 26). The structures were printed and validated using TPU 95A.

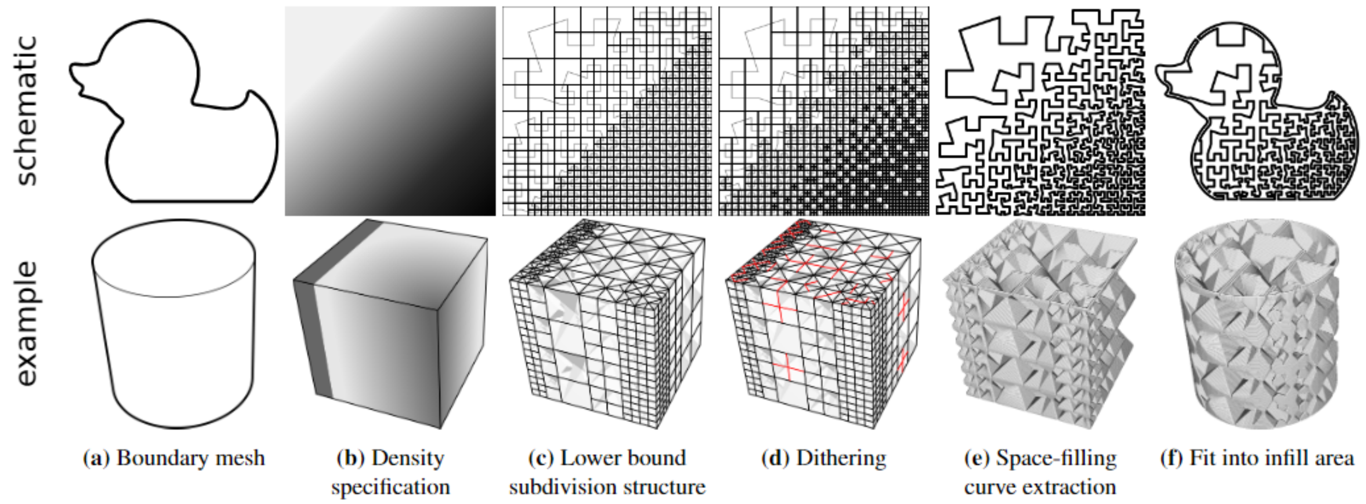


Figure 26. Producing Functionally graded structures using crossfill (Kuipers et al., 2019)

Holmes et al.(2022) explores the potential of flexible, 3D printed gyroid-based metamaterials to replace PU foams. They explore the effect of changing key gyroid structural characteristics on the material's mechanical response (Refer Figure 27). Samples were printed with different cell size and thicknesses in Ninjaflex and X60 TPU filaments and compression tests were performed on them. The study concludes that 3D printed gyroid structures are a viable replacement for soft polyurethane foams, and the direct control of material response can lead to improved optimization. The open structure of gyroid also has potential for greater airflow and egress of fluids when compared to traditional foams.

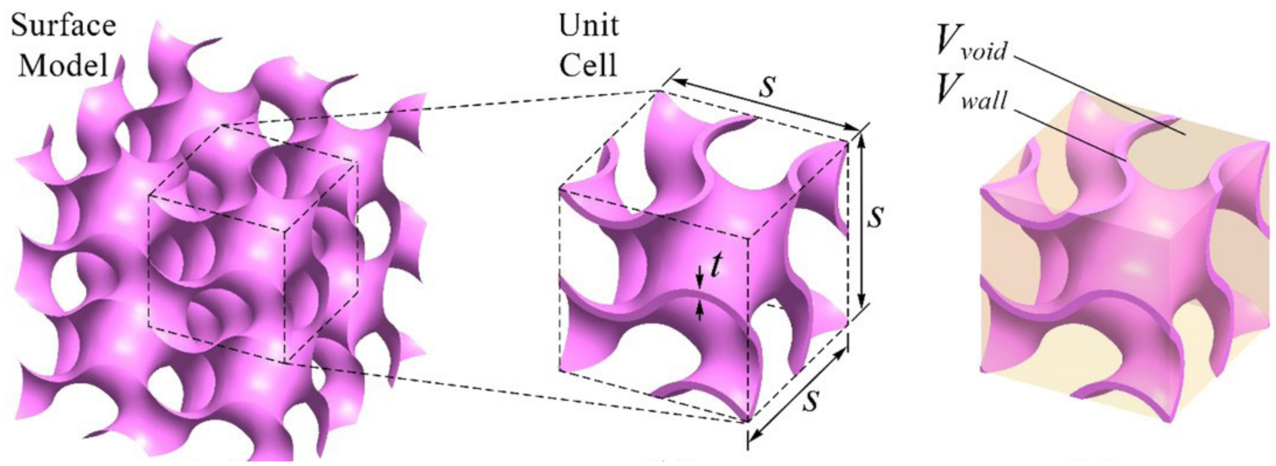


Figure 27. Gyroid lattice structure (Holmes et al., 2022)

Shaikh et al., (2023) studies the effects of customized 3D printed insoles for patients with foot related musculoskeletal ailments. The study was conducted on 200 subjects with varying foot problems. The study used FDM printed TPU 95A insoles (Refer Figure 28). A padding layer of EVA sheet (1mm and 2mm) or PORON(2mm) was adhered on the top layer of the insole (Refer Figure 29). These materials showed excellent durability and satisfactory improvement rate of over 95% of the validated trials. Even after using for 21 months, no visible deformation was seen in the inlay sole. They are highly durable as long as they are not exposed to water, upon which their performance is affected. The study finds FDM is effective for the insoles to be used in daily routine life as they are found to be effective in alleviating pain arising from static weight-bearing activity as well as walking. The SLS method is preferred for high ground reactive force activities such as sports. The study further elaborates that the durability of 3D-printed insoles can be exceptionally good with certain precautionary measures taken by the users.

Figure 28. 3d-printed insoles by Shaikh et al., (2023)

Figure 29. 3d-printed insoles after Padding by Shaikh et al., (2023)

Conclusion

Information regarding the measurement devices offers insight into the available data types, as well as the methodologies and techniques employed to acquire them. 3D scanning and plantar pressure measurement represent the latest and most promising techniques for data extraction.

During insole design, ensuring uniform pressure distribution stands out as a paramount criterion.

The gyroid lattice structure, offering foam-like responsiveness, seems suitable for inlay sole application.

FDM 3D printing of TPU emerges as a cost-effective manufacturing approach that additionally boasts excellent durability.

1.5. Market Analysis

Apart from literature, the commercial footwear products were also explored. This included products that made use of the advantages of additive manufacturing and products that focused on customization.

3D printing is used in the footwear industry for two main purposes:

i. **Personalization:** Creation of customized (allowing for different options) or fully personalized (unique for each user) footwear by collecting data from users.
ii. **Structure Optimization:** Manufacturing shapes and lattice structures that were not possible to be manufactured by conventional methods. This can be done for light weighting, providing unique mechanical responses, or for aesthetics.

The different 3D printed footwear in the market are compared in Figure 30 in terms of the amount of personalisation and structure optimization done

Figure 30. Market Overview

Companies like Zellerfield are producing custom 3D-printed shoes with unique and captivating designs (see Figure 31). These shoes are marketed as fully recyclable and are manufactured without generating any production waste. Caliendo (2023) discusses the rising popularity of 3D-printed sneakers, citing notable brands such as Under Armour, Adidas, Nike, and New Balance.

New Balance employs 3D-printed soles crafted from a proprietary photopolymer known as "rebound resin" (So, 2019). Under Armour is collaborating with EOS to develop advanced laser sintering technology. Nike is partnering with Prodways to explore 3D-printed outsoles, midsoles, and insoles using TPU, which reduces manufacturing time while enhancing performance; Prodways utilizes laser sintering in their process. Adidas has teamed up with Carbon to create the Futurecraft 4D, featuring a latticed midsole designed to provide directional spring for runners. This midsole is crafted using a custom dual-cure urethane resin that is both UV and heat curable (Adam Savage's Tested, 2022). Startup Footprint 3D (Hendrixson, 2017) also attempted to 3D print lattice structures for midsoles. Zoles employs Fused Deposition Modeling (FDM) printing to craft conforming inlay soles; however, they do not capitalize on the potential to manipulate internal structures to achieve heterogeneous material behavior. Aetrex currently offers 3D-printed custom orthotics, utilizing data from 3D scanning and static pressure mapping. These structures are customized locally and then manufactured using powder bed printing (Aetrex, 2023).

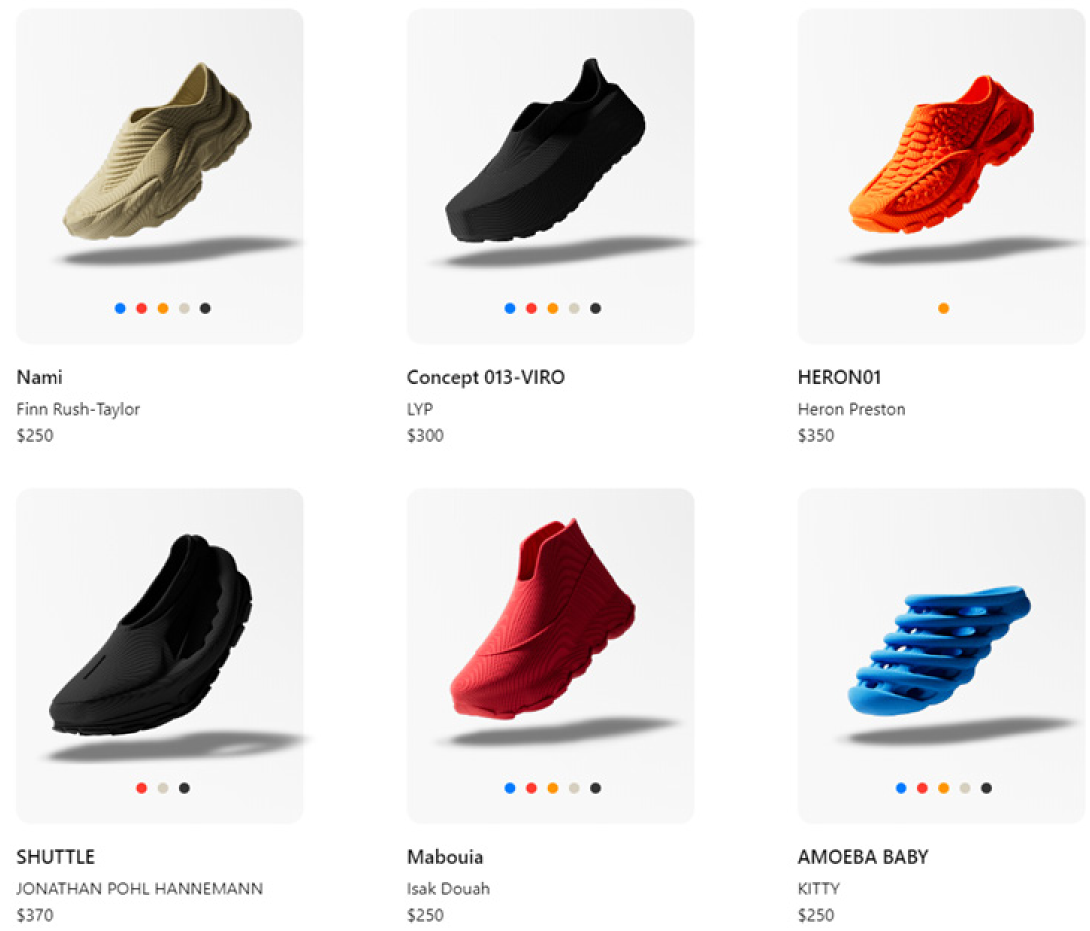


Figure 31. 3D Printed shoes by Zellerfileld (2023)

To see the current processes of manufacturing the inlay soles, the plant of Podolab Hoekschewaard, Rotterdam, a manufacturer of inlay soles was visited. Here the different methods of creation of inlay soles were observed. Conventional methods of production involve either machining from a EVA block or vacuum forming foam sheets to the desired shape. They are also experimenting with different additive manufacturing methods like serialised FDM production and Resin printing of inlay soles. The FDM prints are done at an angle with a conveyor belt printer to aid in serialized production without human interference, enhancing the viability in a commercial production setting (Refer Figure 32 a. and b.). The angling the print head allows for printing inlay soles larger than the print bed and also could provide increased horizontal shear strength. A resin printed orthotic insert produced by PLHW is also shown in Figure 32.c.

a.

b.

c.

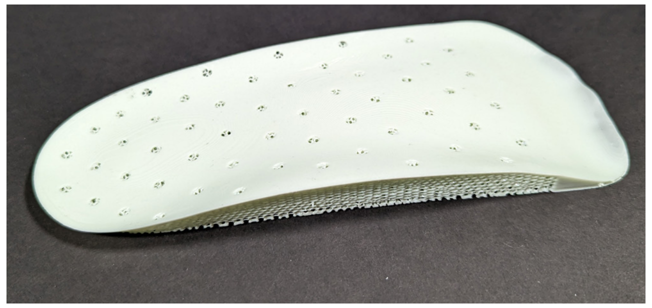


Figure 32. a. b. FDM 3D printed inlay soles c. Resin printed arch support produced by Podolab Hoekschewaard

Conclusion:

3D printing has gained substantial traction in the footwear industry. This technology is being harnessed for both functional and aesthetic purposes. Notably, one of its significant benefits is recyclability, aligning well with the growing demand for sustainable production practices.

The utilization of Fused Deposition Modeling (FDM) for crafting inlay soles has demonstrated cost-effectiveness, prompting a notable shift among manufacturers. FDM allows for intricate lattice structures, optimizing comfort and performance, while also streamlining production processes, resulting in cost reduction.

1.6. Expert Interview

To receive first hand information about the process of designing and customizing inlay soles, apart from the visit to the facilities, an expert interview was conducted with a cardiovascular surgeon who specializes in diabetic foot care. The interview was aimed at gaining insight into understanding what data is collected and how medical footwear are currently designed.

Notes from the interview:

Medical footwear is designed for individuals at a high risk of developing or already having ulcers, possibly due to conditions like diabetes. These ulcers can be indicated by the presence of calluses or corns on the feet. In the prescription of corrective footwear, standing pressure and pressure during gait are recorded using a pressure walkway, resulting in a pedobarograph. While standing, force distribution is typically equal on both feet, but if pain occurs while walking, the body compensates, leading to uneven pressure between the feet. Further gait analysis employs motion cameras and sensors to monitor lower body movements and postures. Ideally, the hip, knee, and ankle joints should align linearly. Additionally, 3D foot scans automatically measure and identify conditions such as claw foot, hammer foot, flat foot, or valgus.

Footwear is designed to correct posture, with the inlay sole aiming to uniformly distribute the load across the plantar surface. High-pressure foot areas are relieved by removing material beneath them, ensuring the newly created cavity's circumference doesn't lead to a new high-pressure region. The feet are subdivided into three parts: Forefoot, Midfoot, and Heel. The heel and forefoot experience greater pressure, with added cushioning and shock absorption in the heel. Arch support is chosen based on the foot's arch height.

In inlay sole design, frictional force between the inlay sole and footwear is another factor to consider, preventing slipping. Given that many patients have neuropathy, the footwear is seam-free and lacks hard surfaces that might cause foot rubbing and pain.

Conclusion:

The interview offered valuable insights into the overarching approach and methodologies adopted within the medical sector when prescribing orthotic insoles. While the project's main emphasis doesn't lie in medical devices, there's potential to draw inspiration from their design process. Leveraging 3D foot scans and pressure data can yield crucial information applicable to personalization. Additionally, the even distribution of loads could enhance comfort not only for non-medical users but also aligns with findings in literature (Ma et al., 2019), (Telfer et al., 2017). Introducing cushioning and shock absorption features to high-pressure areas, such as the heel would be desirable.

2. Define

The Define stage narrows the focus, involving the collection of first-hand data from foot measurements of participants. Ultimately, this leads to the compilation of a List of Requirements from all the amassed information.

2.1. Measurement Session

The subsequent phase of the project involved gathering data pertaining to the foot, aimed at comprehending foot behavior across varying conditions. The accumulated data will undergo analysis to unveil patterns in foot behavior. Notably, participants displaying the most substantial deviations from the average population are chosen. These individuals are selected to aid in the design of personalized inlay sole prototypes within the scope of this project.

Drawing from the literature, market analysis, and interviews, two paramount parameters crucial for inlay sole design emerged: foot shape and plantar pressure distribution. Gathering this data under varied conditions was equally significant for comprehensive insights. To ascertain foot shape, a laser scanner facilitated 3D scans of each foot, while dynamic plantar pressure distribution was determined using an in-shoe pressure measurement system.

Research Question

The aim of the experiment is to analyze how the pressure and shape of the foot vary among different participants and also in different loading conditions.

Participant demographics

As per the input from Bata, the most common safety shoe demographic is– Size 42 males. The results of the test and the project can be adapted to other sizes. The participants recruited are 8 students from the university.
Inclusion criteria: Male with shoe size 42.
The exclusion criteria: Any injury associated with the leg/walking.

Figure 33. Xensor insole pressure sensor

Figure 34. Foot 3D scanning setup

Figure 35. Safety shoes with pressure measurement insoles

Tools & Equipment

- 3D foot scanner
- XSensor insole pressure measurement device with safety shoe
- Lifting load of 4.7 kgs
- Stadiometer
- Weighing scale
- Toe off angle Wedge of 30°

Procedure

The participant is briefed on the measurement process and their signature is obtained in the consent given the consent form.(See Appendix 5) The weight and stature of the participant is measured.

Pressure Measurement:

The participant is given the shoe with the Xsensor and is given 1 minute to be acclimatised to it. Anderson et al. (2020) studies three work based movement tasks, a walk up and down the room, a static standing task and a dynamic standing task . A similar approach was taken here for the pressure measurement.

Figure 36. Gait pressure measurement

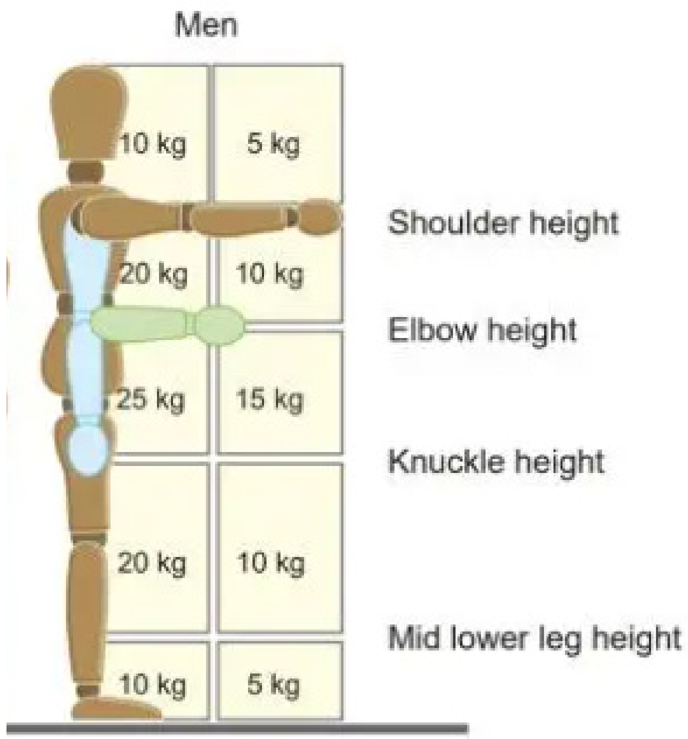


Figure 37. Maximum weight according to HSE

Figure 38. Lifting setup

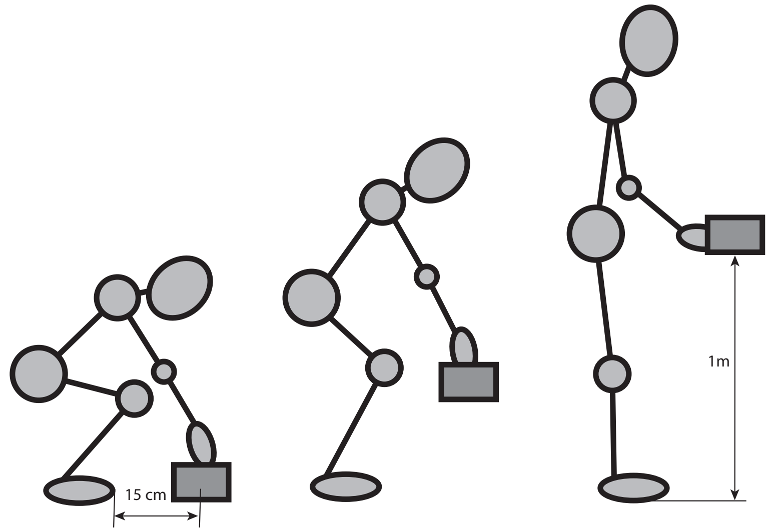


Figure 39. Lifting Posture

The Pressure is Recorded for the following conditions:
- Static standing position.
- Walking for a distance of 34m.
- Lifting a Load.

For the standing position, the participant is instructed to stand in a way that equally distributes the weight on both feet and the data is recorded for a time period of 5 seconds.
For the second measurement, the participant is asked to walk at a pace comfortable to them without looking at the ground (Hayda, 1994). For the lifting measurement, a standard weight of 4.7kg was chosen in accordance with the guidelines from "Manual handling at work" by Health and Safety Executive of the UK (Refer Figure 37). The weight is placed at a distance of 15cm from the toe of the shoe. The participant is asked to lift the weight with both hands from the ground to a height of 1m and keep it back down while bending the knee and back straight (Refer Figure 38&39). Lifting was added as it is a typical worker activity and gives an added data set as measurement during level walking alone cannot be considered to fully define the plantar pressure affecting a foot (Rozema et al., 1996).

3D Scanning

3D scans of the foot are taken in the following conditions for both feet:
- Neutral Position – Full Body weight.
- Neutral Position – No Load
- Neutral Position – Normal Standing (50% load)
- Toe-off position – 50% load at an angle of 30°

The different loading conditions help understand the change in shape of the foot with load. The toe-off position further helps determine the treadline. The participant is asked to distribute the weight to the best of his ability using the weighing scale provided as a reference. The angle of toe off is ensured using a wooden wedge. The angle of 30 deg was chosen based on observation of typical toe-off of the participants. The wedge is placed to angle the foot and then is taken out during the scanning.

Figure 28.(a)Wedge (b) Wedge used to position toe-off

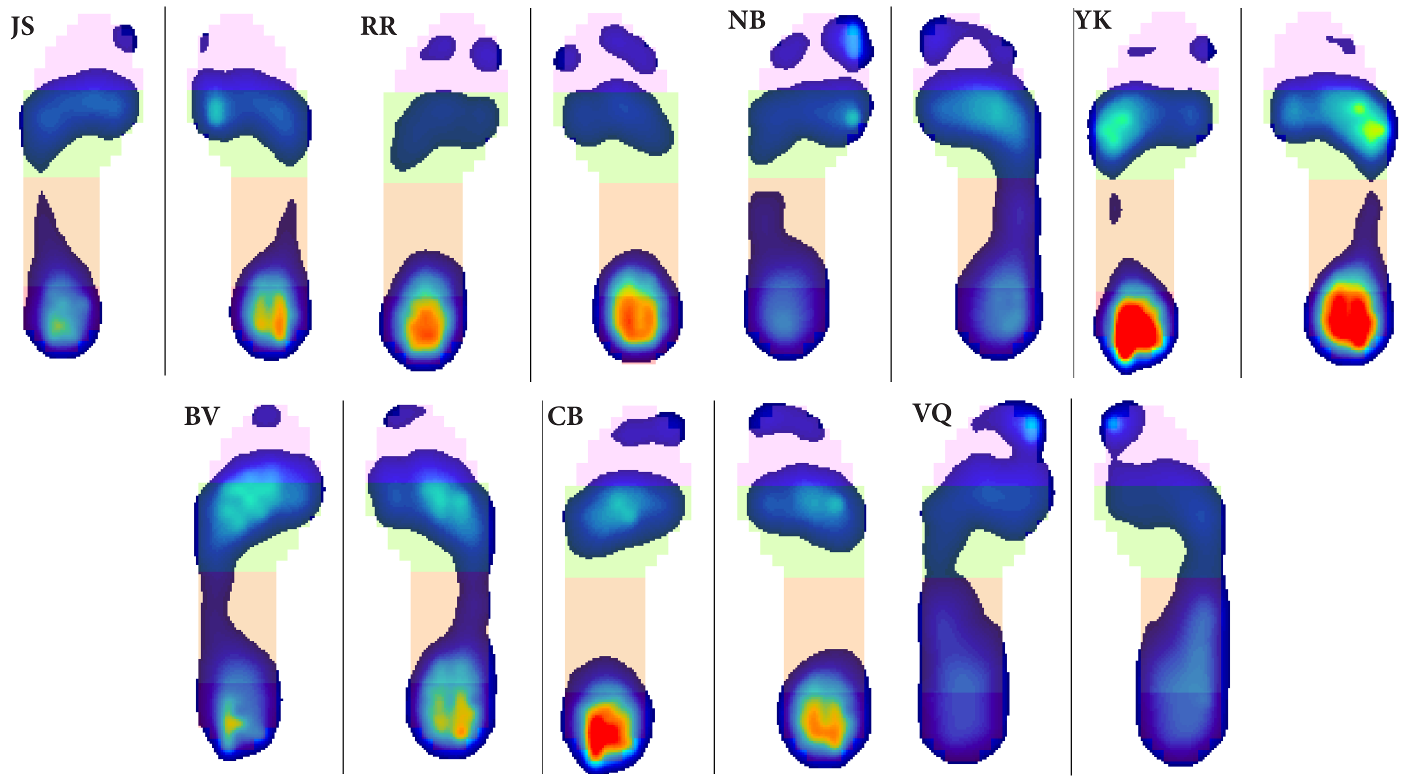


Figure 29. Pressure Distribution While Standing for Different Participants

Data Acquisition:

Dynamic pressure data was recorded at a rate of 75Hz with a resolution of 235 sensels/foot for all the three activities .Example of the data collected is shown in Figure 29.

The 3D scans were taken with a laser foot scanner . An example of 3D scan is showed in Figure 30,

The analysis and processing of the collected data is detailed in the chapter 2.2.

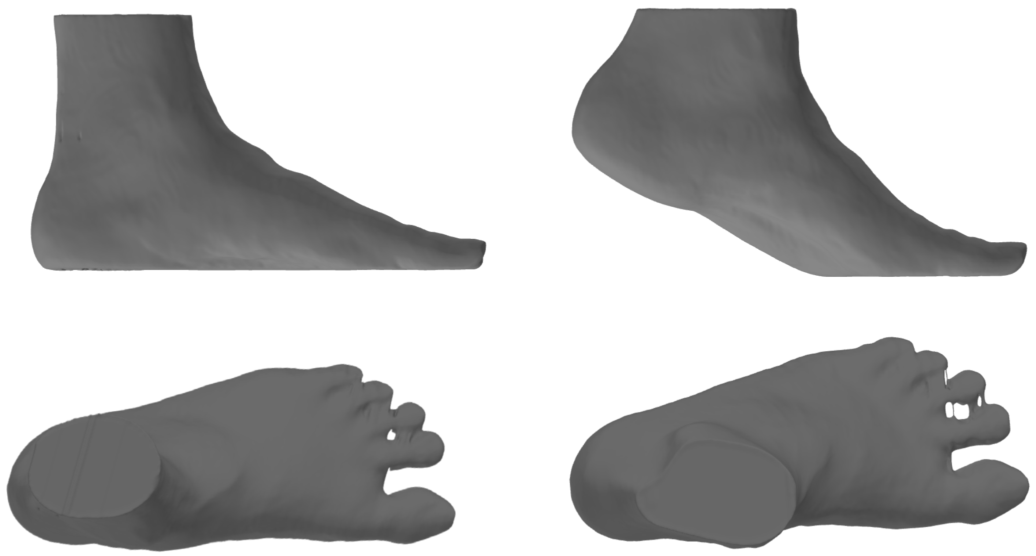


Figure 30. 3D Scans for participant BV in fully loaded and toe-off conditions

2.2. Data Analysis

General observations:

3D Scans

In the loaded condition, the length of the foot increased by 2-3mm ,width of the foot increased by 1-5mm and the general height of the foot reduced by 3-5mm compared to no load condition . It was observed that there was little variation between half body weight and full body weight loading, while there was a huge difference between the no load condition and neutral load condition. The toe off scan is used to determine the treadline (line at which the inlay sole is designed to flex).

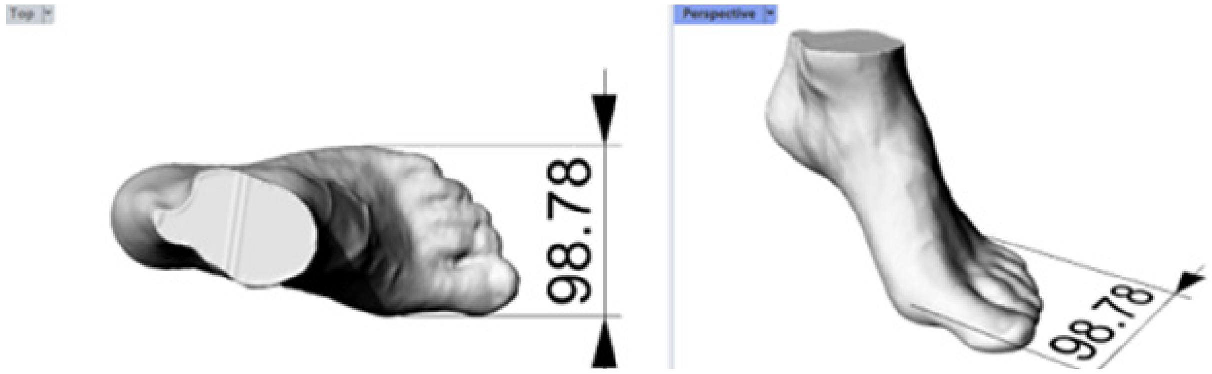


Figure 40. Toe off forefoot width measurement

Pressure Scans

The pressure scan showed differences between the load distribution and peak pressures in the left and right foot of the same individual. Among the activities measured, the highest pressure was observed during walking with peak pressure 200-600% more than standing or lifting. Also since walking was the most common activity a worker has to perform, this was identified to be the most crucial. Comparing the peak pressures and average pressures give the same pressure hotspot areas.(See Figure 41) For the lifting condition, increased pressure is observed under the phalanges but is less than (45-60% of) Peak walking pressure.

A few parameters from each of the participants were extracted and tabulated in Table 1 to identify the ones who stood out. One frame where the load was equally distributed between both feet was extracted from the standing data for this comparison as this allows to understand the difference in pressure hotspots in between the left and right feet as well. Manual measurements of the length and width of the foot were also done in the CAD program according to the standard outlined in (Kristina, 2022). The parameters were Peak pressure/ weight, Average Pressure/weight, Foot contact area, arch height and the length and width of the feet in standing condition and width of the forefoot during toe off (See Fig 40). Visual comparison was also done on the pedobarographic chart, the superimposition of the foot 3D scan onto a standard Bata size 42 inlay sole, and the pressure distribution in the forefoot during the toe-off condition.

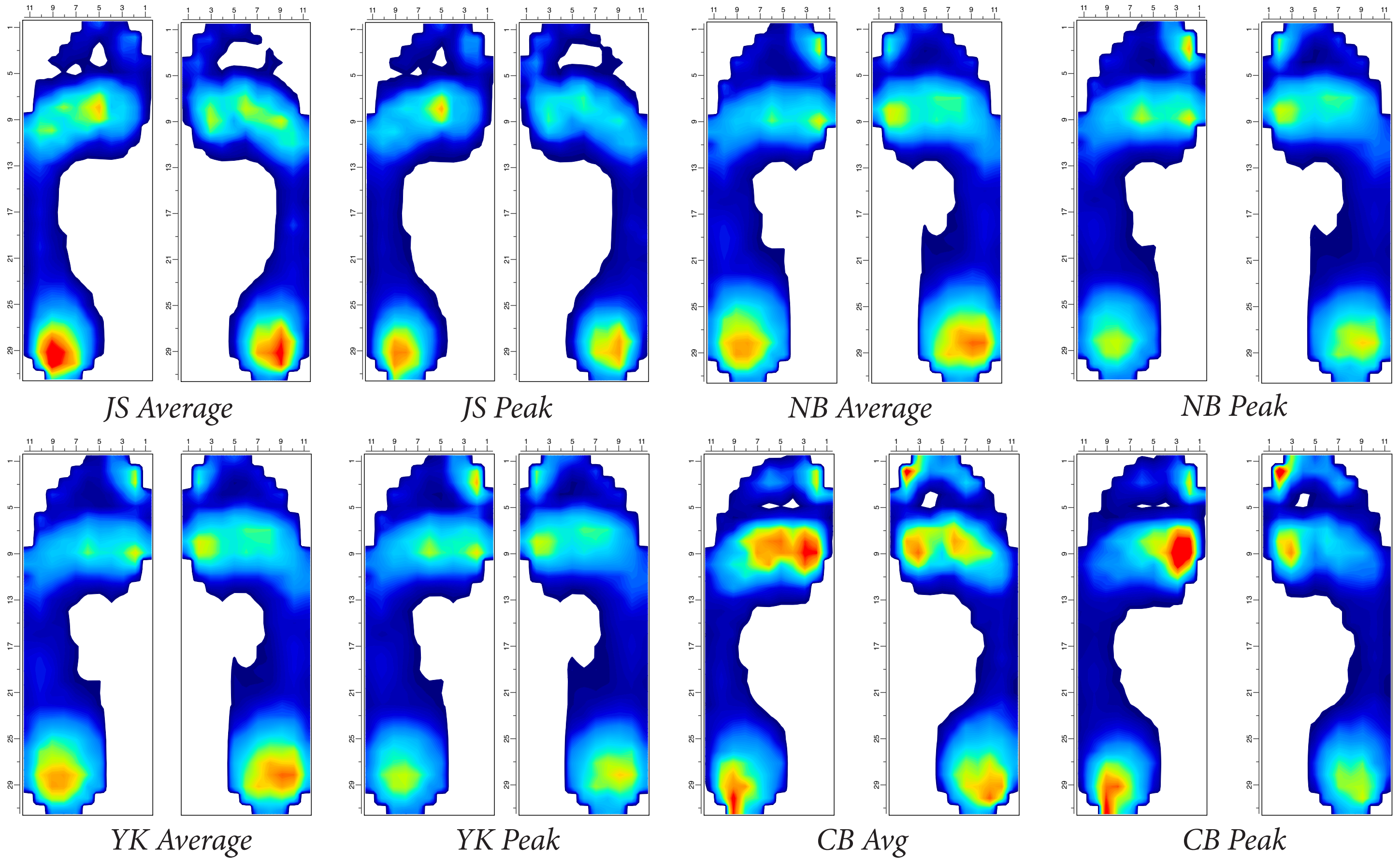


Figure 41. Peak and Average pressure hotspots from participants JS, NB, YK, and CB. Here the figures are scaled differently to identify the hotspots. It is observed that they occur at the same location.

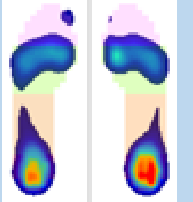
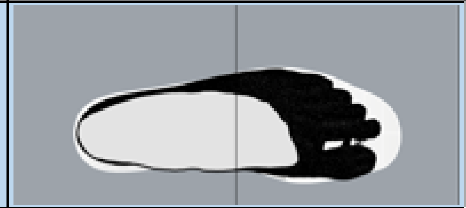
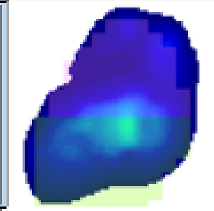
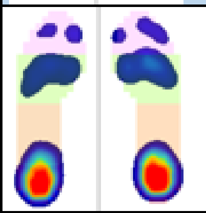
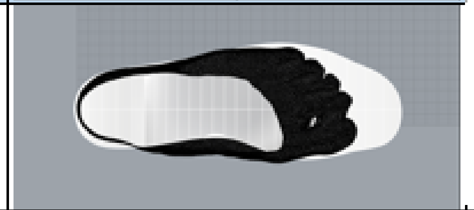
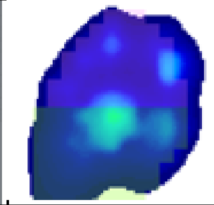
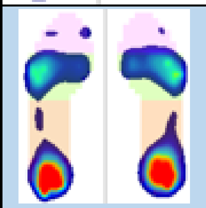
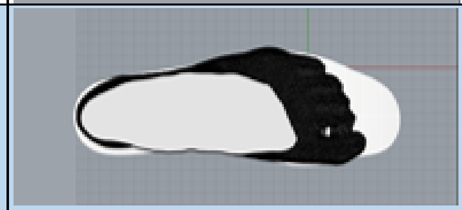
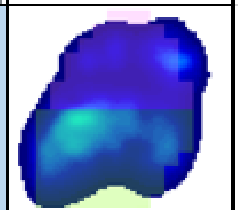
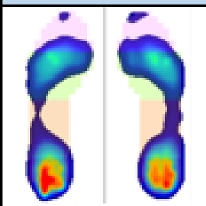
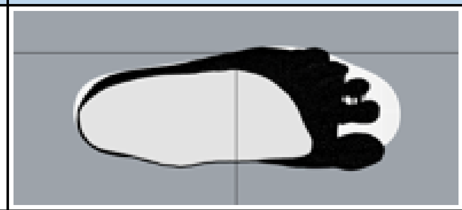
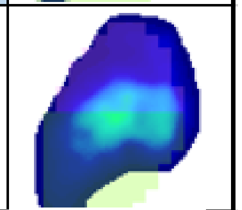
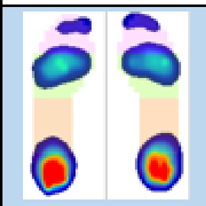
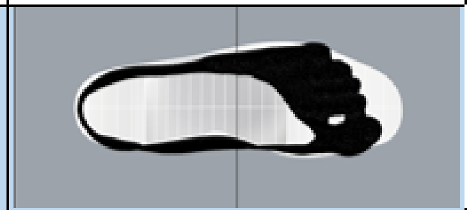
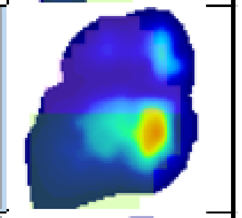
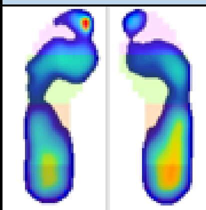
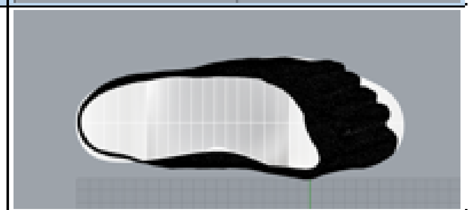
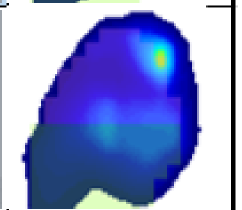
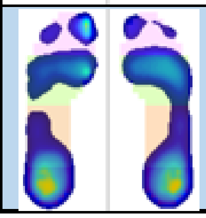
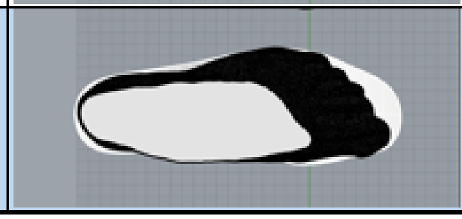
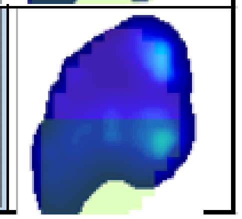
Participant Overview															
Paticipant name	Weight (kg)	Height (cm)	Peak pressure (kPa)	Average pressure (kPa)	Peak pressure/ weight	Avg pressure/ weight	Contact area (cm2)	Pressure distribution	Foot Length (mm)	Foot Width (mm)	Arch Height (mm)	Forefoot Width during toe off (mm)	Foot Length/Width	3D Model	Peak forefoot pressure -toeoff
JS	58.6	168.5	130	33	2.2	0.56	S		264	97	21.5	95	2.72		
RR	60.4	165	143	38	2.4	0.63	78.08		245	101	6.5	102	2.43		
YK	73.9	179	244	43	3.3	0.58	83.2		251	103	21	100.5	2.44		
BV	78	172.4	146	35	1.9	0.45	101.12		265	109	17.5	105	2.43		
CB	71.8	176.4	215	43	3.0	0.60	81.92		261	93	17	92.5	2.81		
VQ	76.5	185	67	24	0.9	0.31	124.16		276	107	14	102	2.58		
NB	72.4	191.2	76	28	1.0	0.39	104.96		268	99	15.2	99	2.71		

Table 1. Participant Overview

Participant selection:

The selection of the participants for which prototypes would be created and tested was made based on the following criteria:

1. **Suitability for 42XW inlay sole:** The first parameter considered was a proper fit in the standard Bata size 42XW inlay sole. Based on length, RR had a short foot and VQ had a long foot for size 42. BV and VQ would require XXW size shoes as they had very wide feet.
2. **Differences in foot shape and flexing line:** JS and CB has a narrow forefoot that suits geometry personalization and fitting improvement. YK and NB had a full fitting forefoot and a different location of flexing. Another interesting factor was the Greek foot shape of JS compared to the Roman and Egyptian.
3. **Differences in Length/Width Ratio:** It was important to have a variety of length/width ratio among the selected participants so that the potential for customization can be explored.
4. **High peak pressure/weight:** The important function of an inlay sole is to reduce peak pressure, thus the selected participants should have high peak pressures compared to their body weight.

The 3rd and 4th parameters were mapped in the scatter plot (Refer figure 29). The participants JS, CB, NB and YK are selected for further testing.

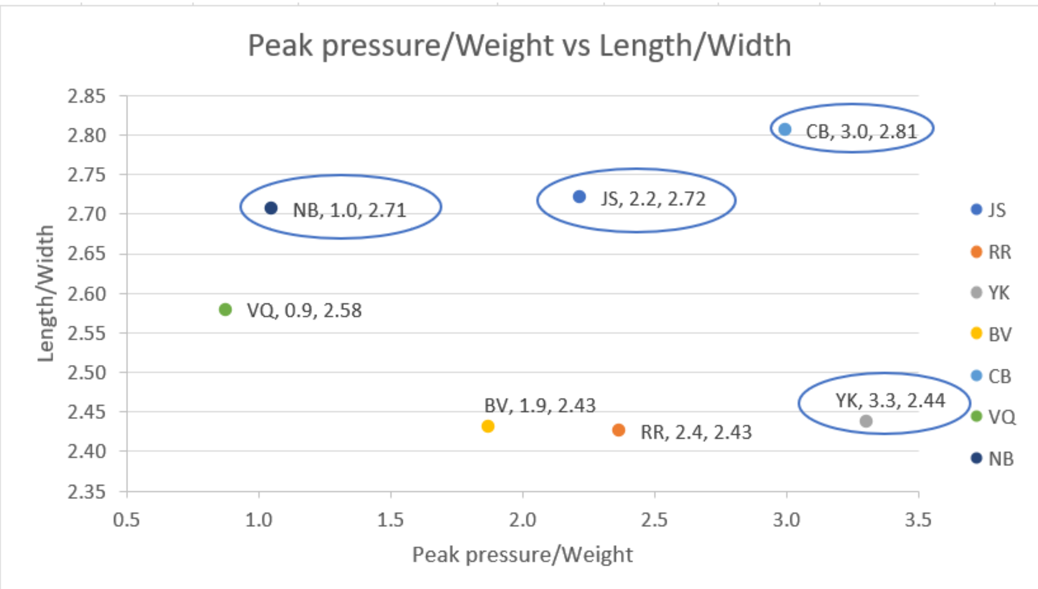


Figure 42. Creation of simplified mid-foot and heel model

Detailed Analysis:

<u>Pressure Data</u>

Gait analysis was performed by isolating frames. The threshold used is frames from a heel strike load >=68.9 N to a Toe-off load<68.9. From the gait cycles identified using this criteria, 20 steps from the middle of the activity is isolated to create an averaged stance. This stride is used in further analysis. The different stances during gait for participant NB is shown in Figure 43.

To perform a comparison, the peak pressures recorded by each sensel during the gait is mapped. The peak and average pressures were extracted from this. The pressure data from the four selected participants is in Table 2.

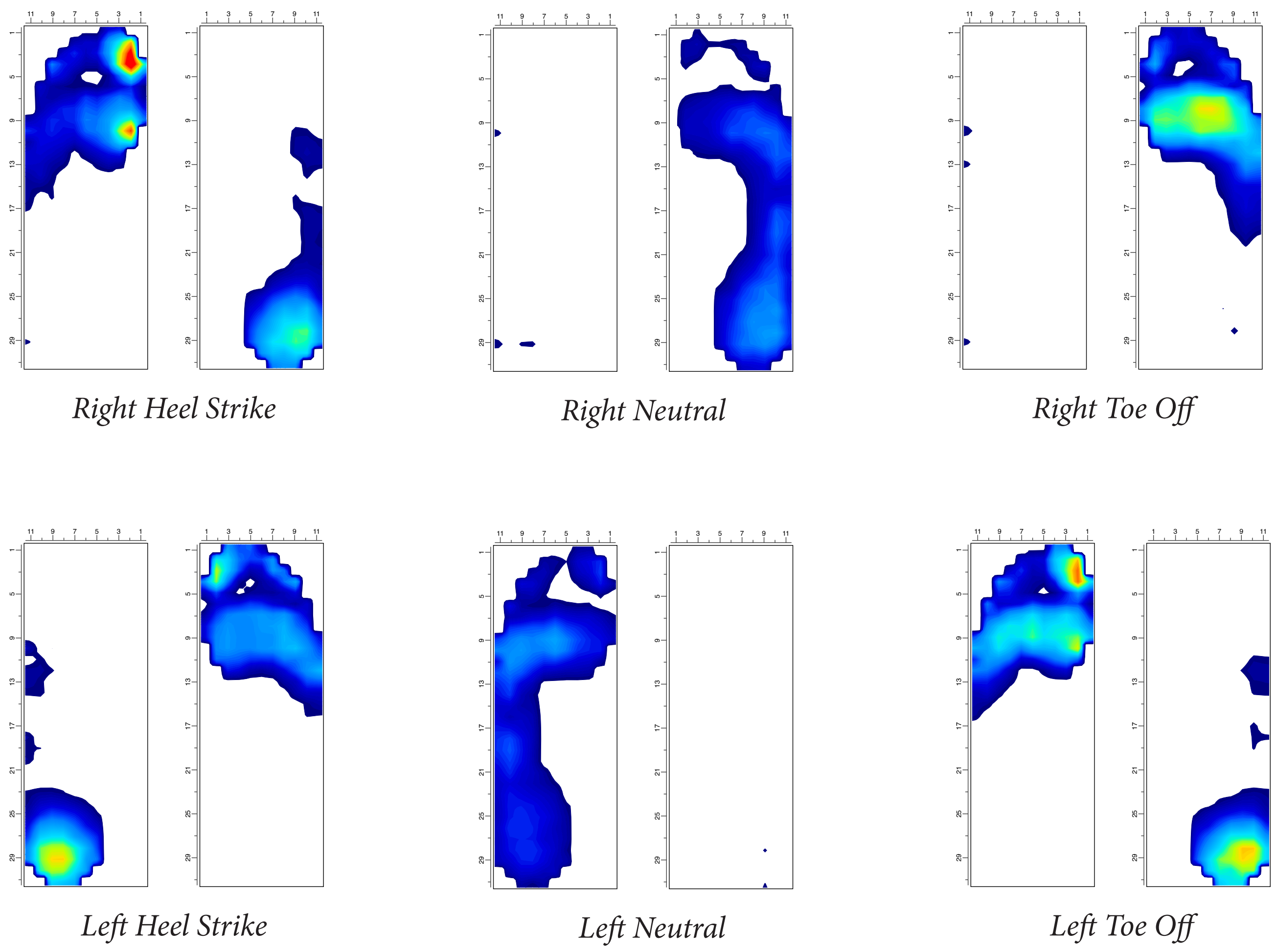


Figure 43. Different stances while walking for NB

Participant	Leg	Pose	Peak Pressure (kPa)	Average Pressure (kPa)
JS	Left	Standing	95.6	28.43
		Walking	368.82	93.65
		Lift	192.62	47.12
	Right	Standing	138.06	35.25
		Walking	345.33	97.26
		Lift	224	52.01
YK	Left	Standing	244.31	43.5
		Walking	625.59	116.28
		Lift	283.6	57.21
	Right	Standing	149.45	42.08
		Walking	351.5	119.67
		Lift	230.62	64.65
CB	Left	Standing	215.35	43.79
		Walking	584.03	124.42
		Lift	305.95	63.67
	Right	Standing	127.53	38.75
		Walking	666.66	119.42
		Lift	172.26	51.39
NB	Left	Standing	76.49	29.49
		Walking	446.73	93.17
		Lift	209.64	42.06
	Right	Standing	81.26	31.16
		Walking	360.71	95.79
		Lift	130.46	40.46

Table 2. Pressure Data

a. b. c.

Figure 44. JS left foot a.50% body weight b. No load c. Full body weight

3D Scan:

The 3D scans were imported into Rhino and measurements of key dimensions were taken to compare how they vary in different loading conditions. The 3D Scans of one foot of JS is shown in Figure 44. The measurements of the selected 4 participants are presented in Table 3.

Participant	Leg	Pose	Length (mm)	Width (mm)	Arch height (mm)
JS	Left	Loaded	264	97	10
		No load	261	92	14
		Neutral	264	96	13
	Right	Loaded	262	97	9.5
		No load	260.5	92.5	14
		Neutral	262.5	95.5	9.5
YK	Left	Loaded	253	101	13.5
		No load	251	99.5	16
		Neutral	253	100	14
	Right	Loaded	253.5	101.5	18
		No load	251	100	26
		Neutral	254.5	101	21
CB	Left	Loaded	263	98	14
		No load	261.7	97	15
		Neutral	261.5	96.5	14
	Right	Loaded	264.5	97.5	13
		No load	260.5	94	15
		Neutral	263	97	14
NB	Left	Loaded	268	99	15
		No load	265	96	17
		Neutral	267	98	15
	Right	Loaded	267	99	15
		No load	264	95.5	17
		Neutral	266	98	16.5

Table 3. 3D Scan measurement data

Conclusion

Considerable disparities were noticeable in both foot shape and pressure distribution among the participants. This underscores the significance of personalization.

The pressure data accentuates significantly high peak pressures experienced during walking. Considering a factor of safety, the inlay sole should be engineered to endure a minimum of 2MPa of pressure.

The acquired data will stand as a valuable foundation for designing adaptable features that can cater to the diverse range of foot types.

2.3. List of Requirements

A list of requirements for the inlay sole is compiled from all the conclusions from the research. The list of requirements is clustered across different categories as prescribed by Boeijen et al., (2021).

1.Performance	i. Pressure Distribution: The inlay soles should be able to redistribute pressure uniformly across the foot to prevent the development of pressure points or discomfort. ii. Shock absorption: The inlay soles should have adequate shock-absorbing properties to reduce the impact on the feet and lower limbs. iii. Arch support: The inlay soles should provide proper arch support to promote foot stability and prevent overpronation or excessive foot movement. iv. Cushioning: The inlay soles should radially distribute loads and offer sufficient cushioning to enhance comfort during prolonged wear. v. Stability: The inlay soles should provide anti-torsion and midfoot stability. vi. Moisture Management: The inlay soles should have moisture-wicking properties to keep the feet dry and prevent discomfort or fungal infections. vii. Odor Control: The inlay soles should be designed to minimize odor-causing bacteria and maintain freshness. viii. Electrostatic Discharge: The inlay soles should be able to incorporate ESD.
2.Environment	i. The inlay sole should be able to resist peak pressures upto 2MPa and shear forces during gait. ii. Chemical Resistance: The inlay soles should be resistant to chemicals and substances commonly encountered in the wearer's work environment. iii. Heat Resistance: The inlay soles should withstand temperatures upto 60°C without deformation or degradation. iv. Heat Conductivity: The inlay soles should not trap in heat and act as an insulator. v. Slip resistance: The inlays soles should not slip inside the shoe
3.Life in Service	i. Durability: The inlay soles should be durable and able to withstand regular wear and tear or 10hours per day. ii. Longevity: The inlay soles should maintain their performance and structural integrity over time for atleast a year. iii. Easy maintanance: The inlay soles should be easy to wash/clean
4.Market Fit	i. Personalisation: The inlay soles should target mass personalisation for providing better fit and comfort compared to typical inlay soles. ii. Non medical Device: The inlay soles should not be a medical orthotic device iii. Cost Effective: The price should be comparable to customizable inlay soles available in the market.
5.Size and Weight	i. Dimensions: The inlay soles should be of the dimensions specified by Bata Industrials. ii. Fit: Should be easy to insert into the shoe and fit snugly. iii. Lightweight Design: The inlay soles should be lightweight to avoid adding unnecessary bulk and should not cause fatigue during extended wear.
6.Materials	i. Skin safe: The materials should be non-allergenic and hypoallergenic to minimize the risk of allergic reactions or skin irritations for wearers with sensitive skin. ii. Comfortable Upper Layer: The upper layer of the inlay sole should be made from a durable material that can resist abrasion and provide comfort. iii. Breathability: The materials used should have good breathability to allow air circulation and prevent excessive moisture buildup, keeping the feet cool and dry. iv. Recycled Materials: It is desirable to make use of some percentage of recycled materials for production
7.Manufacturing	i. The production method has to be suitable for mass personalisation ii. The initial investment costs should be justifiable for a low production volume. iii. The manufacturing method should be easily adaptable to different styles and requirements of shoes/inlay soles
8.End of life	i. Enviroment friendly: The materials used should be recyclable or disposed easily. ii. Material Separation: Different materials should be easily separable to aid in recycling and disposal.

3. Develop

The Develop stage starts from establishing the design boundaries. Testing is done determine the direction. Ideation is done to explore different possible options in the solution space and finally concrete design choices are made which better defines the solution space.

3.1. Design boundaries

The new inlay sole has to be within the design guidelines set by Bata. The shape of the design has to be the same as Bata's size 42XW inlay sole. The thickness of the new inlay sole at different points is also defined by the Dimensions of the shoe variant that can be produced by Bata (Refer Figure 44) (See Chapter 5.1 for details). Thus the outer dimensions of the inlay sole are defined.

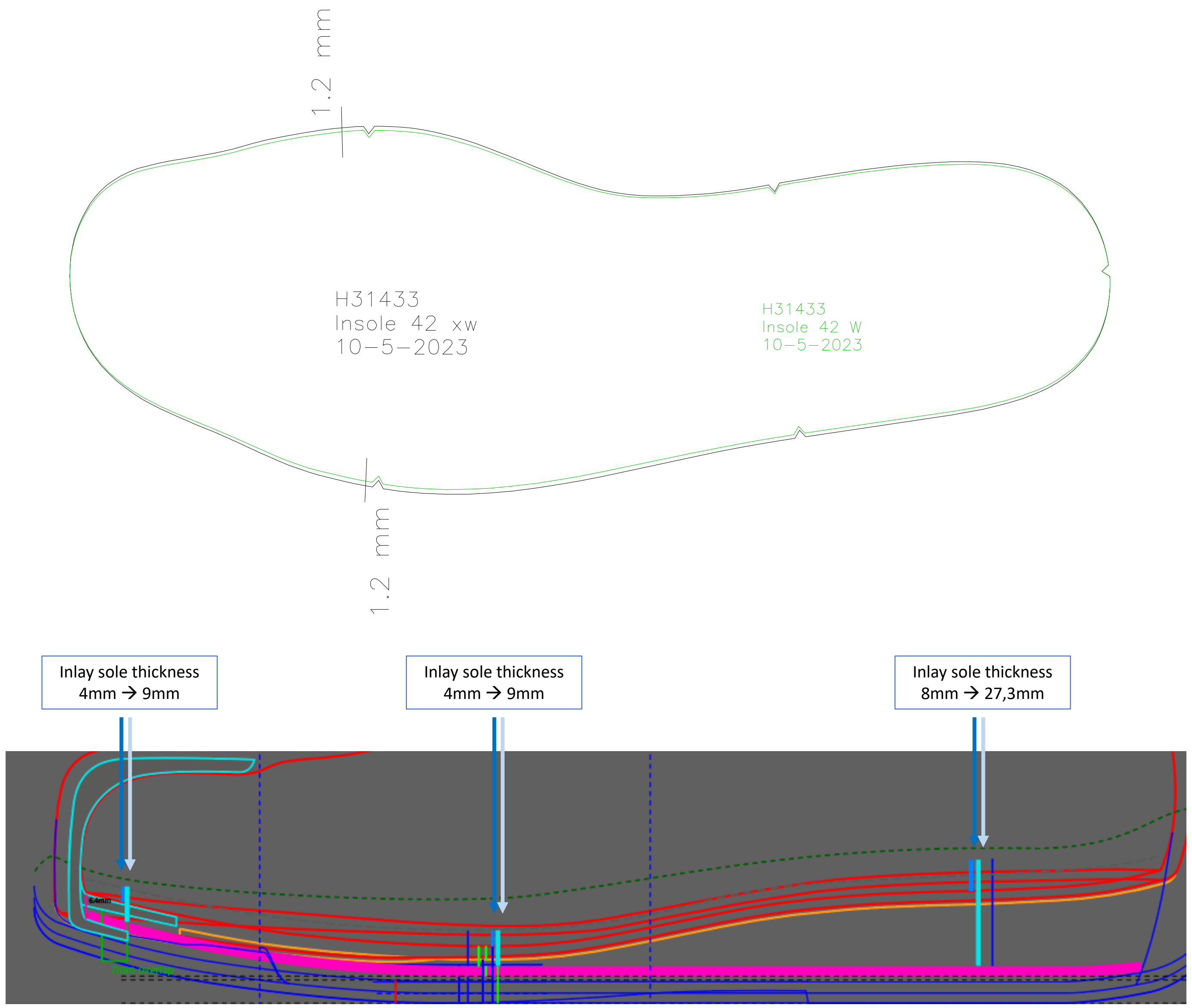


Figure 45. Inlay sole dimensions

3.2. Mechanical Testing

From the research, FDM printed gyroid lattice structures made of TPU was identified to be suitable for inlay soles as it showed properties similar to PU foam (Holmes et al., 2022). This can also be made into a Functionally Graded Material with different stiffness/cushioning at different locations by changing the thickness and the lattice dimensions. To test its behavior, a compression test is employed.

Research Question

To study how changing the unit cell dimensions affect the response, compression tests were performed on printed samples of TPU.

Samples:

Since non uniform unit cells are used in the design, the test was done in 2 variations.

i) Keeping the z dimension (vertical) of the unit cell constant at 25mm and changing the X-Y dimensions
{(5X5X25), (10X10X25), (25X25X25)}

ii) Keeping X-Y dimensions of the unit cell constant at 25mm and varying the z dimension,
{(25X25X5),(25X25X10),(25X25X25),(25X25X30),(25X25X50)}

All the samples were created using NTop and were cuboids of the dimensions 80mmx80mmx9mm (Refer Figure 32a&b). The length and width were chosen so that it could be loaded into the testing setup with tool diameter 60mm without the walls affecting the result. The thickness of 9mm was chosen to represent the thickness of the forefoot area of the inlay sole, which is the

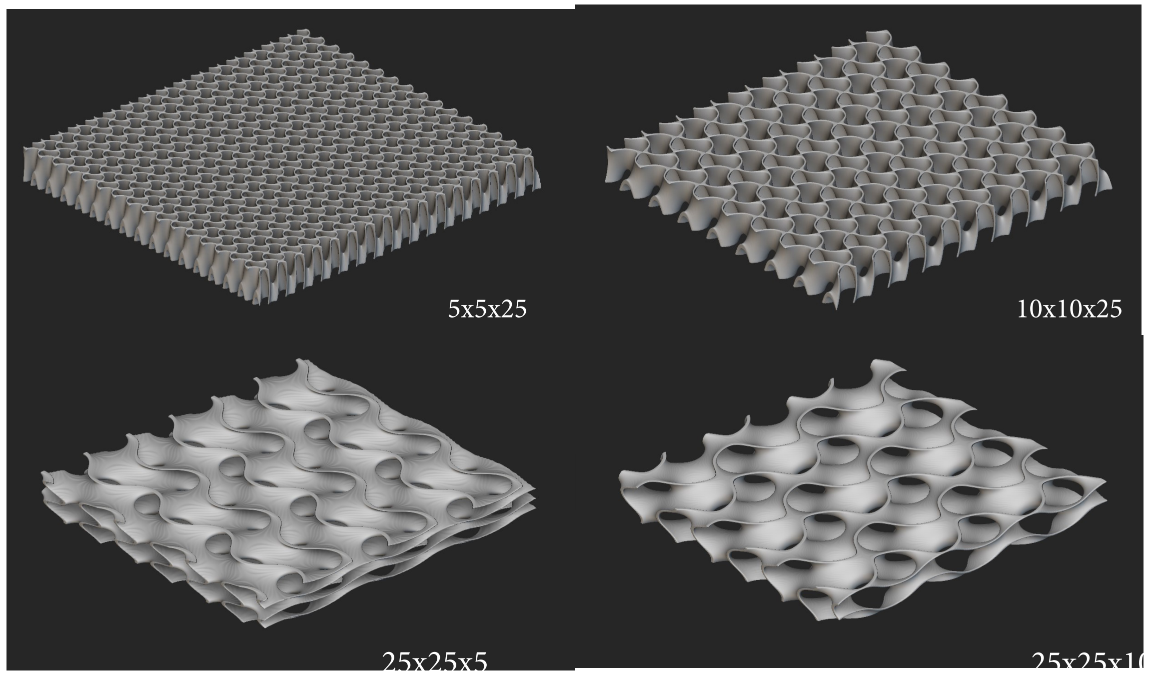


Figure 46. a. Internal Lattice structure of the samples tested

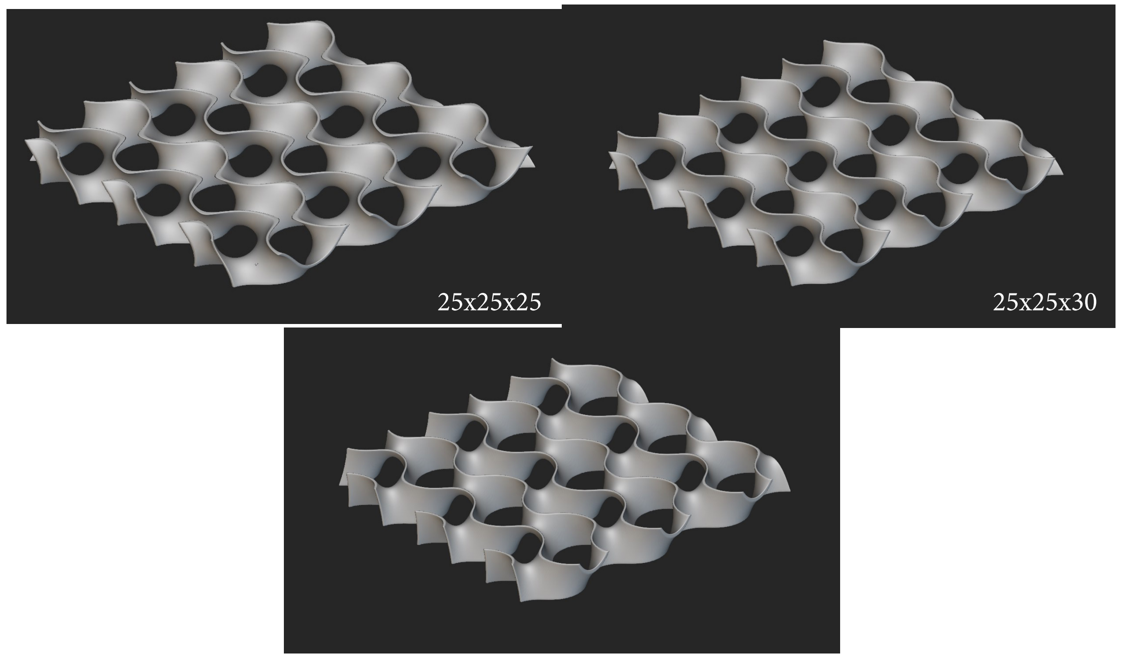


Figure 46. b. Internal Lattice structure of the samples tested

area of focus for this project. The top and bottom Walls were given a thickness of 1mm. The samples were printed with TPU 95A.

Methodology:

The test was done according to the methodology proposed by Holmes et al. (2022) following the international standards for Polymeric materials, cellular flexible – Determination of stress-strain characteristic in compression – Part 1: Low-density materials BS EN ISO 3386–1:1997+A1:2010 and Part 2: High-density materials BS EN ISO 3386–2:1998+A1:2010.

The strain rate for testing was taken as 5mm/min. Since the thickness of the sample is only 9mm, a maximum strain of 55% was taken (5mm travel) which would provide the force values of interest. A 10kN load cell was chosen and the test was performed on a Zwick machine.

Results:

Table 4 shows the force reactions at 1mm, 2mm and 5mm displacement. The results of the compression test is given in Figure 36. The compression of the gyroids were characterised by an initial distributed elastic response, followed by a period of sequential layer-on-layer collapse, and a final densification stage once all layers were closed on one another. Also see Appendix 4 for individual force-displacement graphs..

Inference:

The testing results have affirmed that the behavior of the gyroid infill TPU is similar to that of PU foam. Cell dimensions ranging from 5x5x10 to 30x30x30 would offer the desired cushioning effect for the inlay soles. Furthermore, the process of printing samples for testing facilitated experimenting with various printing settings. This experimentation aimed to identify optimal configurations that yield good print quality while minimizing errors.

TPU Shore 95A						
Unit Cell Size	Pressure (kPa)			Force (N)		
	d=1mm	d=3mm	d=5mm	d=1mm	d=3mm	d=5mm
25x25x5	7	31	681	19	87	1926
25x25x10	40	70	230	115	197	650
25x25x25	91	94	221	259	267	627
25x25x30	63	63	168	178	178	475
25x25x50	12	77	77	36	218	215
5x5x25	935	769	2356	2643	2175	6662
10x10x25	472	348	1029	1335	983	2910

Table 4. Pressure and force reactions

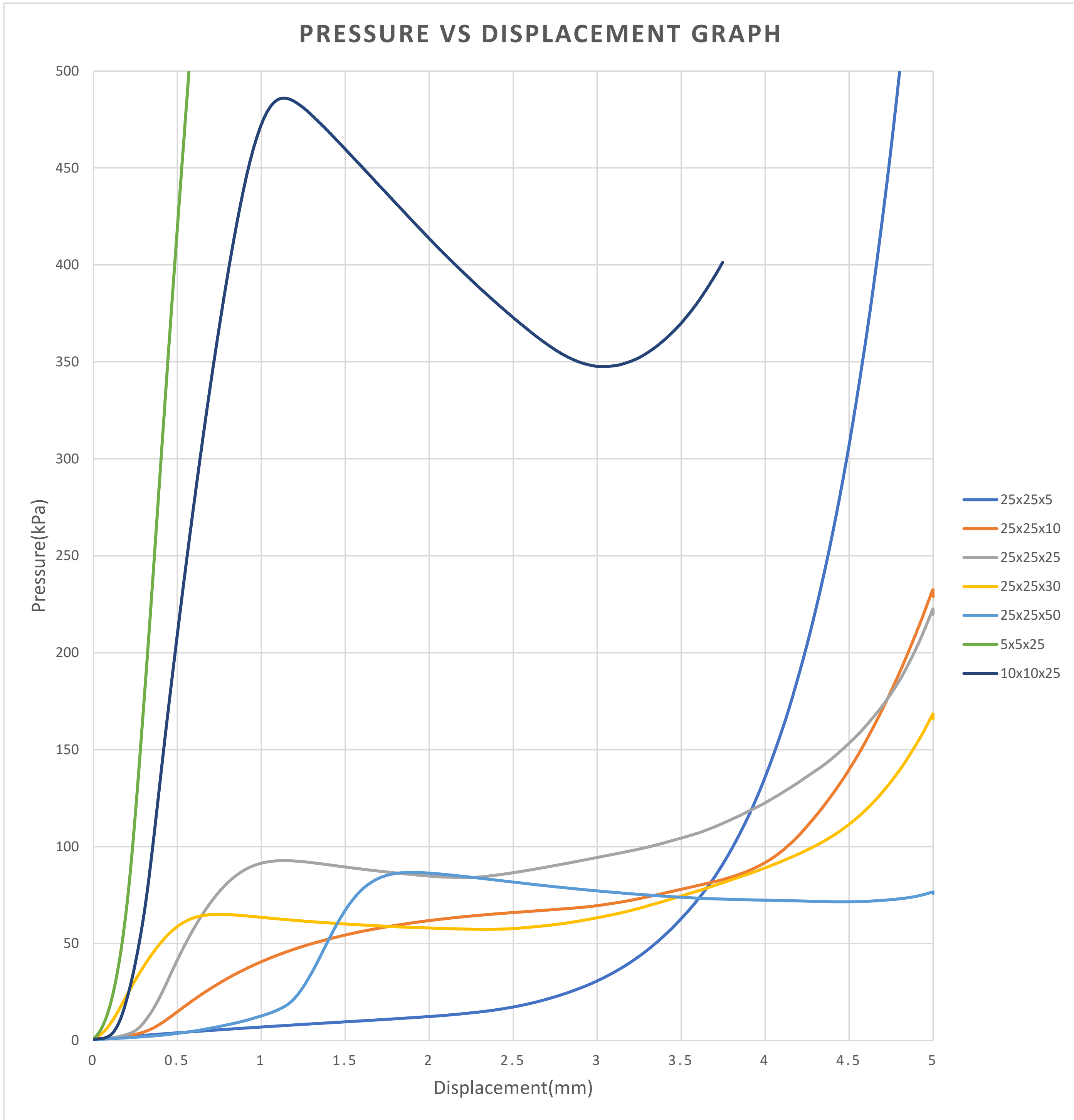


Figure 47. Pressure vs Displacement Graph for all samples

3.3. Morphological Chart

To help in the ideation process, a morphological chart was made. The main functional requirements of the inlay sole are extracted from the list of requirements and possible solutions were listed down.

Functions:

1) Pressure redistribution:

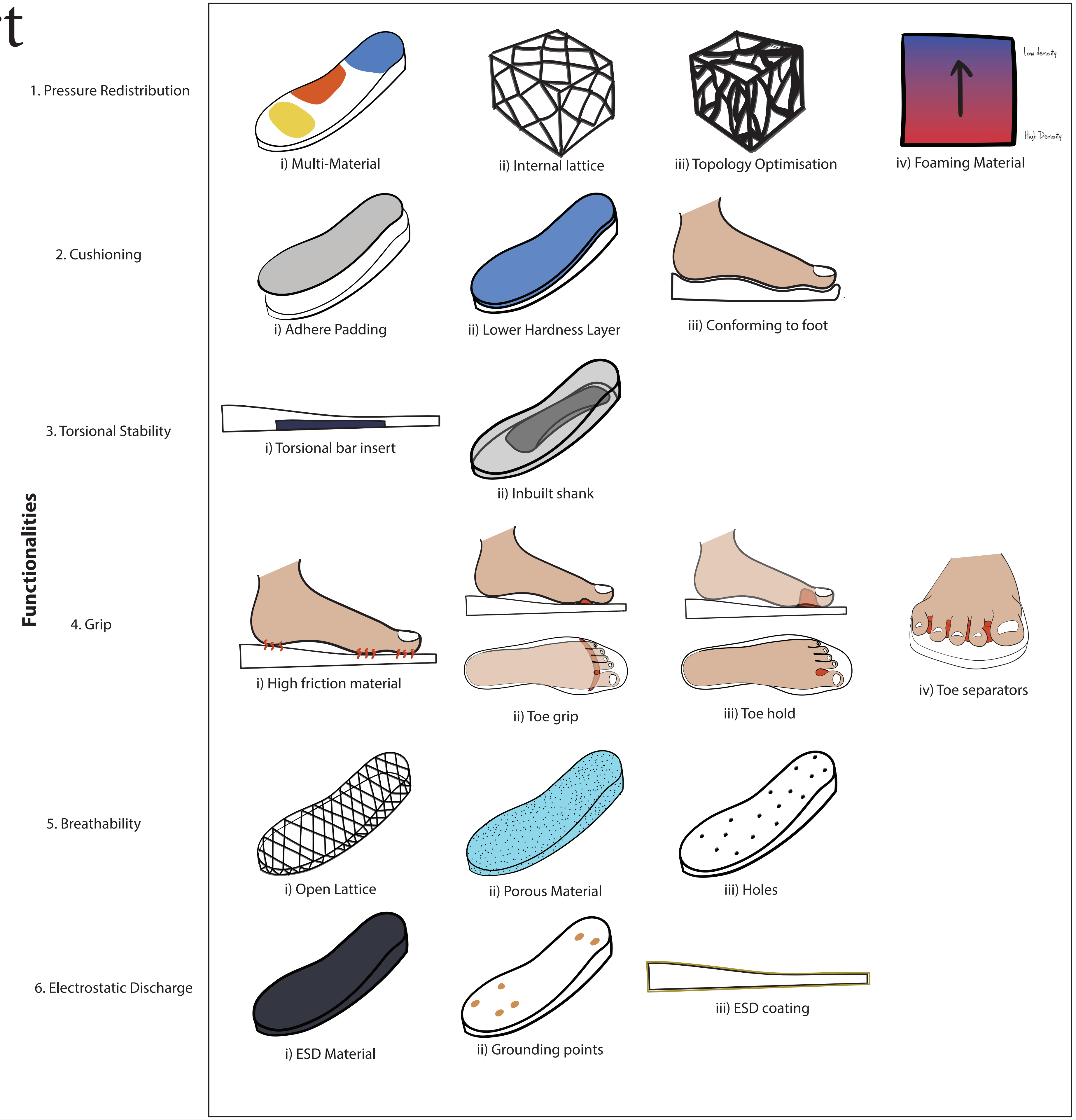
An important function of the insole that helps reduce pain and prevent medical condition is to uniformly distribute the pressure throughout the plantar foot. This function requires

i. Multi-Material : Different areas of the inlay sole can be made from different materials. High Pressure areas can be made from softer material and low pressure areas can be made of harder materials
ii. Internal Lattice: The internal construction of the inlay sole can be made of lattice structures and the response at a location can be changed by changing either the thickness or the size of the lattice at specific area. Increasing the thickness or reducing the size, increases overall density and stiffness at a location.
iii. Topology optimization. Topology optimization can be done on the internal structure of the inlay sole to give the optimal response at each location.
iv. Active foaming materials: Foaming materials are 3D printable materials whose density and hardness changes based on the temperature at which it is deposited. Different temperature of can be given in different zones to vary the response.

2) Cushioning:

It is also important to radially distribute the load in the foot at each point

i. Adhere Padding: A padding layer can be adhered as the topmost layer of the inlay sole which comes in contact with the foot. The padding can be made of textile, EVA foam, PORON or even leather. Shaikh et al. (2023) shows TPU inlay soles with a padding layer also shows excellent durability.
ii. Low hardness layer: The area of the inlay sole in contact with the foot can be designed to be made of a material of low hardness. This can be done by using a multi material print or active foaming.
iii. Conforming to foot: Another way to radially distribute the load is to ensure that every point of the inlay sole is tangent to the point of contact of the foot. This can be done by molding the contact surface of the inlay sole in the shape of the foot.



3) **Torsional Stability:**
When the foot undergoes rotational forces during movements such as cutting, pivoting, or quick changes in direction, torsional stability helps to provide support and prevent excessive twisting or rolling of the foot inside the shoe.
i. Inserts: A separate torsional bar or shank can be fitted onto the inlay sole.
ii. Internal shank: A shank can be built directly into the structure of the inlay sole.
iii.

4) **Forefoot grip:**
It is important that the foot should not slip on the inlay sole, hence sufficient grip has to be provided, especially in the inlay sole area.
i. High friction material: The layer in contact with the foot can be made of a material that provides high friction with the foot to ensure good grip.
ii. Toe grip: A grip bar can be provided under the toes to provide extra grip. Nakano et al., (2017) suggest that insoles with a toe-grip bar contribute to improvements in toe-grip strength and toe flexibility.
iii. Toe hold: A toe hold similar to those given in sandals can be provided between the big toe and second toe to enhance grip.
iv. Toe separators: Toe separators can be provided. Along with increasing the grip, this also helps to maintain space between the toes which eliminates the buildup of sweat and prevents fungal infections. This also aligns the forefoot and may help in better pressure distribution.

5) **Breathability:**
Another important functionality of the inlay sole is to allow ventilation and not trap heat and moisture in the foot.
i. Open lattice: By having an open lattice structure of the inlay sole, the free flow of air can be ensured.
ii. Porous material: The inlay sole material can be porous enough to allow air to pass through it.
iii. Holes: The inlay soles can have holes throughout it which allows for air to pass through.

6) **Electrostatic Discharge:**
For safety shoes, electrostatic discharge is usually provided in the soles to prevent static charge buildup in the body which could potentially damage equipment.
i. ESD Material: The inlay sole can be completely made of a material that provides ESD. For FDM 3D printing, options in TPU like 3DXstat and Essentium TPU 95A-Z ESD are available.
ii. Grounding Points: Certain points can be added in the surface of the inlay sole which provides a conductive path for the charge to dissipate
iii. ESD coating. The inlay sole can be coated with an ESD material through techniques like physical vapor deposition or vacuum deposition. The inlay sole can also be covered with EVA carbon.

Different elements from the morphological chart were combined and different combinations explored to come up with the final design.

The best identified method to capitalize on the data to provide a good level of comfort is to make use of the 3D Scan data to customize the shape of the inlay sole to provide good support and comfort throughout the foot and use the pressure data obtained to customize the internal construction of the inlay sole to remove pressure hotspots and redistribute the pressure uniformly in the foot.
This is illustrated in Figure 48.

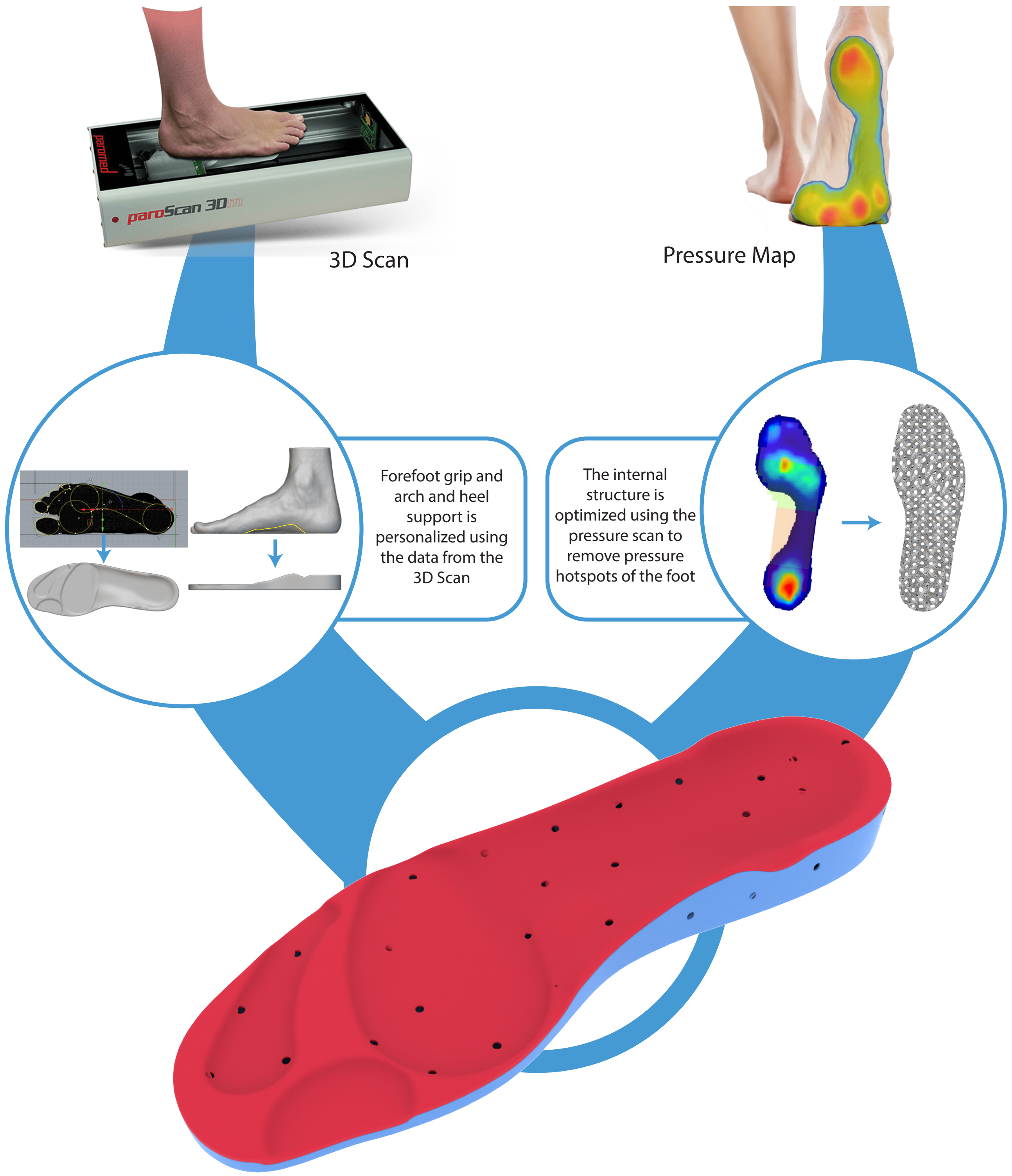


Figure 48. Pressure vs Displacement Graph for all samples

3.4. Design Choices

New development in the field of sensors, design and manufacturing provides a number of options in the design and manufacturing while implementing personalization of inlay soles. Within the scope of the project it is not possible to exhaustively evaluate all the possible options. Table 5 provides a list of specific design choices that were made to set the direction of the project, its reasoning, and possible alternate directions that can be explored.

Design Choices	Reasoning	Alternate directions for future
Pressure taken while walking	• Walking showed much higher pressures compared to standing and static lifting of an object. • Walking was identified as the most common worker activity.	Specific task-related postures can be identified and designed for depending on the specific type of work.
TPU Material for inlay sole	• TPU is one of the most common materials used for flexible 3D printing. • Printed TPU inlay soles are found to have excellent durability. • There are different variations of TPU available which have a variety of shore hardness and features like ESD that is allows for experimentation	Different flexible materials like other TPEs, PEBA, EPU, PP etc. can be explored.
Internal structure of Gyroid Lattice	• The mechanical testing shows that TPU with a gyroid lattice shows foam like response and identifies it as an alternative to foam. • Gyroid structures can be printed continuously and without supports. • Gyroid has an open lattice structure, providing excellent breathability. • The response from the structure can be controlled by changing the unit cell thickness and size.	Other types of lattices like Voronoi, crossfill, diamond lattice, etc. can be explored for better performance.
Fused Deposition Modeling for production	• FDM is the most common and easily accessible form of 3D printing. • The initial investment and running cost of FDM printers are extremely low. • A range of flexible material filaments are readily available to be purchased for FDM printers. • The printers allow for printing of thin walls.	Printing methods such as Resin Printing, SLS, SLA, Polyjet etc. can be explored

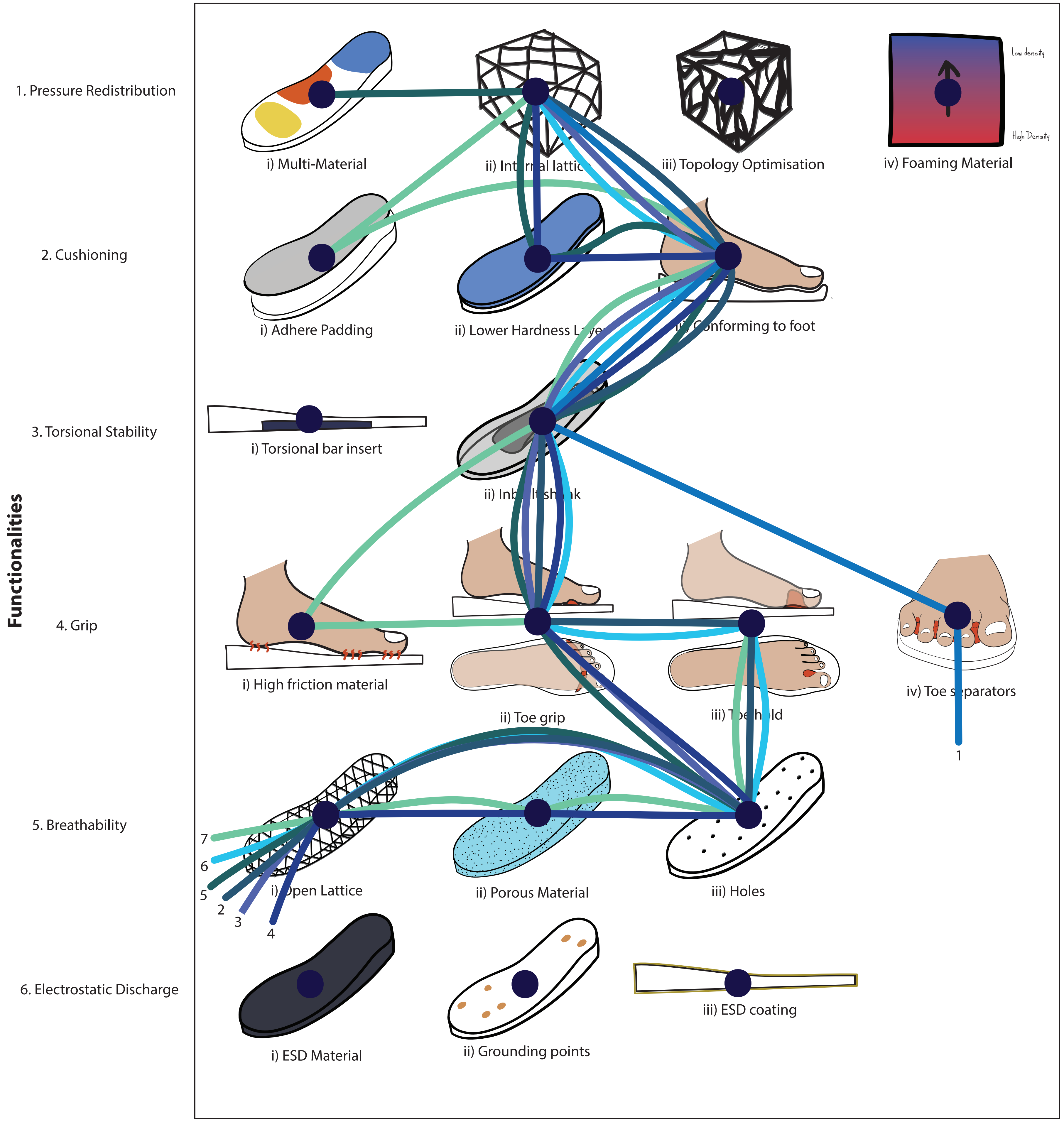
Table 5. Design Choices, Reasoning and Possible alternatives

4. Deliver

The Deliver stage fixes overarching design choices, iterates on potential solutions, and ultimately arrives at a workflow.

4.1. Prototype overview

In this chapter a visual overview of the elements used in each prototype numbered 1 to 7 is shown. This helps contextualize the solution space explored. The Prototypes in detail are explained in the following section

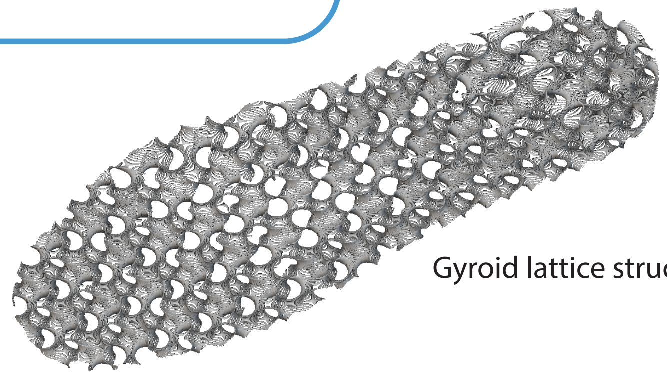


4.2. Prototypes

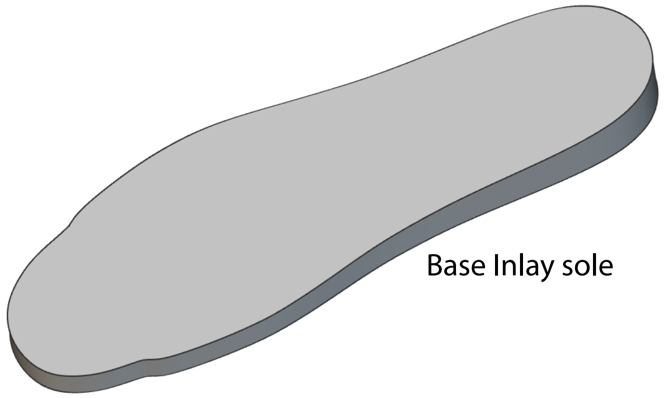
1. Proof of concept

Initially, a proof of concept prototype was made to validate the design methodolgy. A sample foot model and sample pressure data were used as input. The base inlay sole was defined by having a constant thickness in the shape of the shoe last.
A boolean subtraction of the foot model was done on the Base inlay sole to create the shape. The internal gyroid latticeis is customized by varying the unit cell thickness and size.
Two prototypes 1A and 1B was printed with different unit cell ranges to test the cushioning properties.

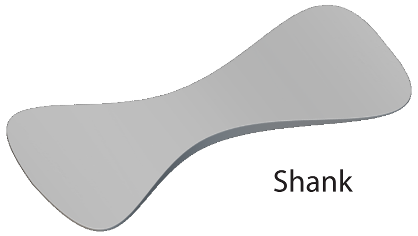
Elements from Morphological Chart:
1.ii , 2.iii, 3.ii, 4.iv



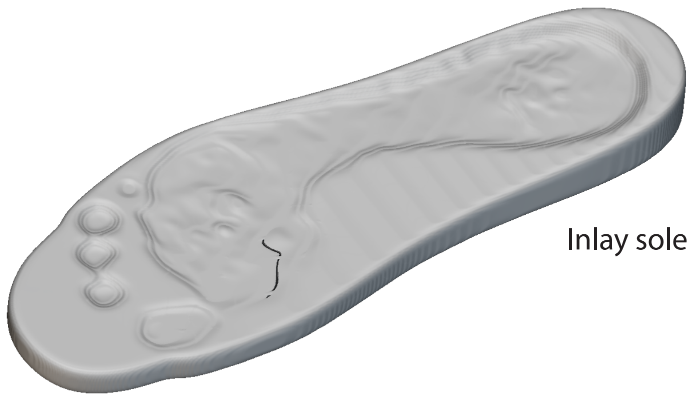
Gyroid lattice structure



Base Inlay sole



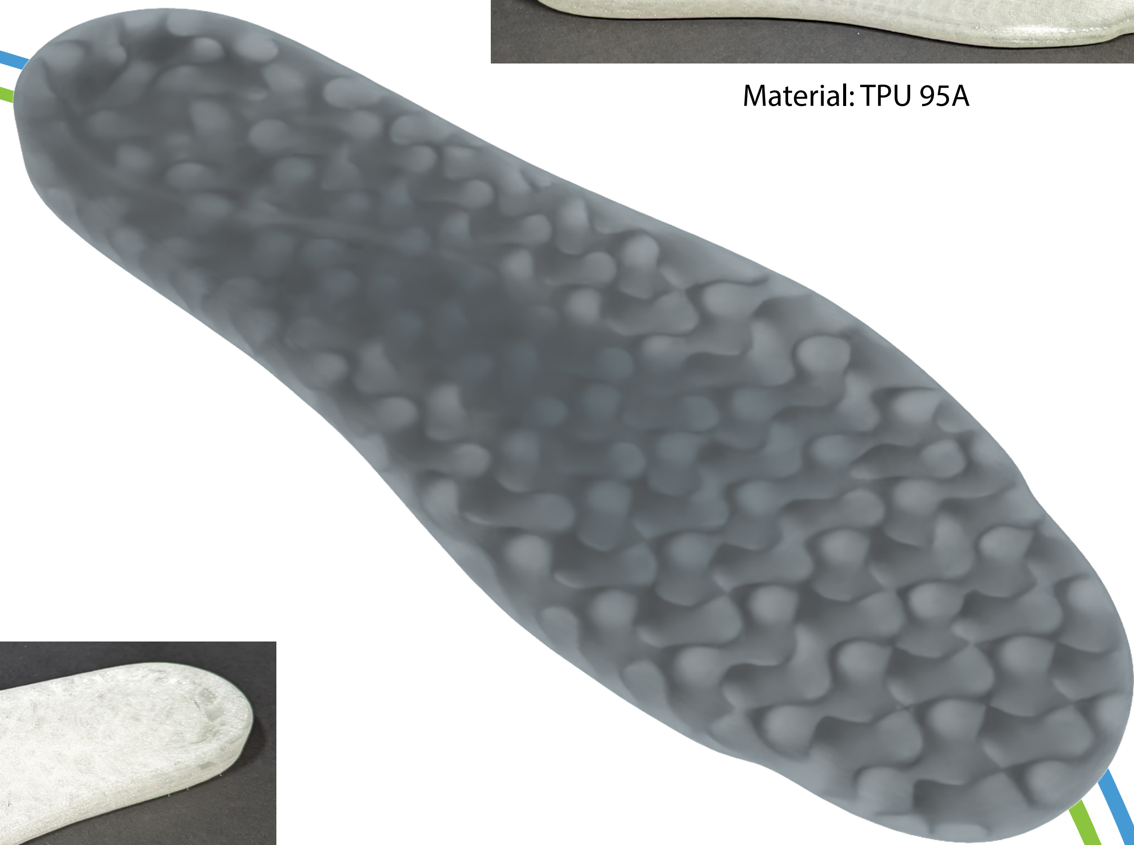
Shank



Inlay sole surface

Prototype 1B

Material: TPU 95A

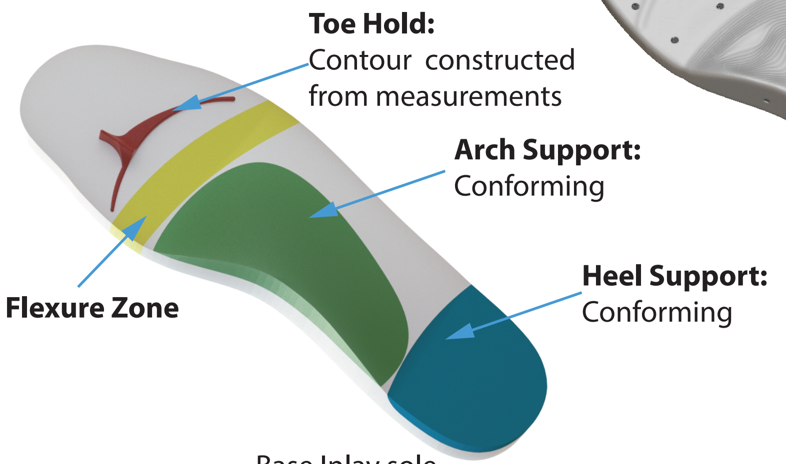


Prototype 1A

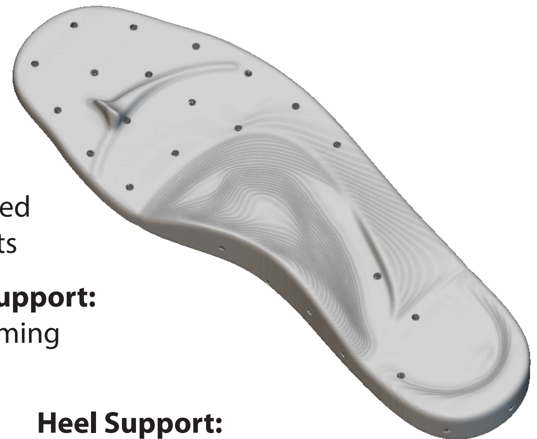
Material: TPU 95A

Prototype 1 proved the feasibility of the design and manufacturing techniques that can be used to produce the inlay soles. Through analysing the two different infills in Prototype 1A and 1B, the range of the unit cells that can provide required comfort was shown to be between 15mmX15mmX15mm and 35mmX35mmX35mm for TPU 95A.

Prototype 2A



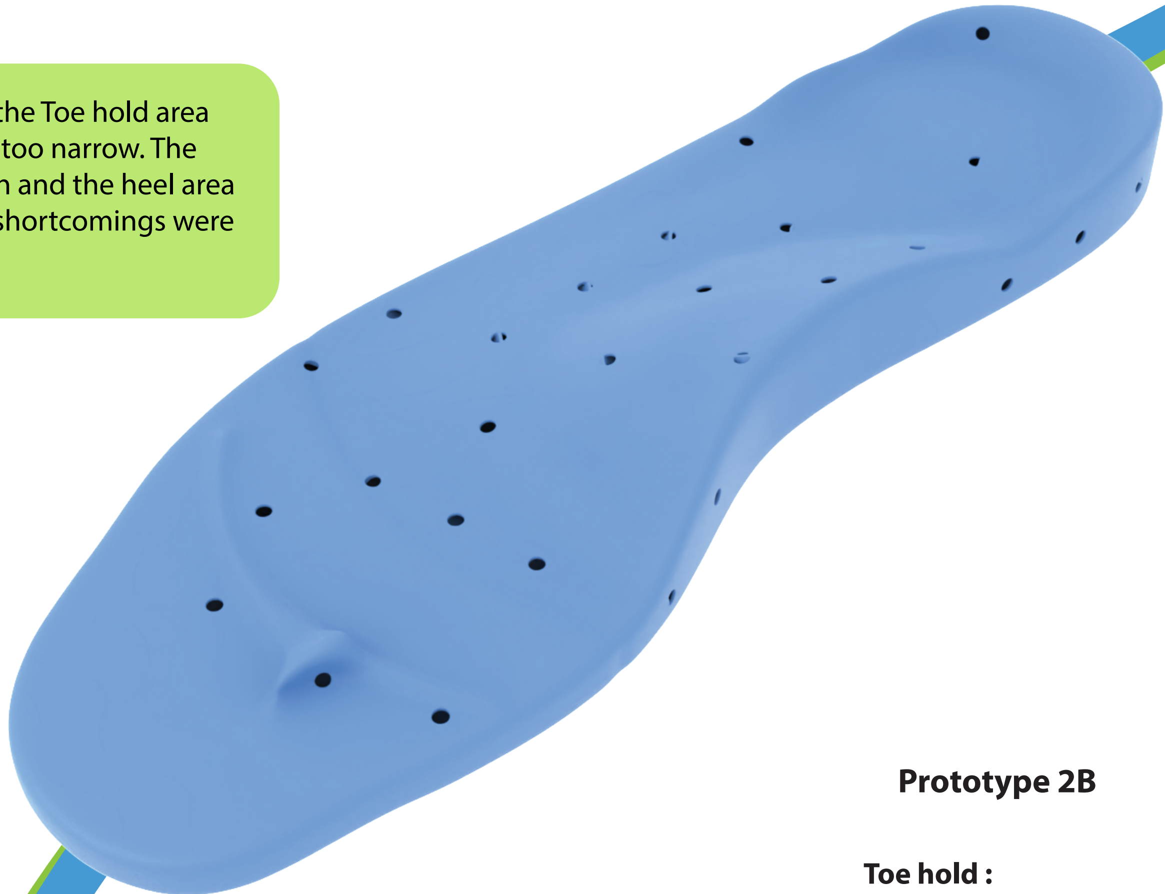
Base Inlay sole



Inlay sole surface

Material: TPU 95A

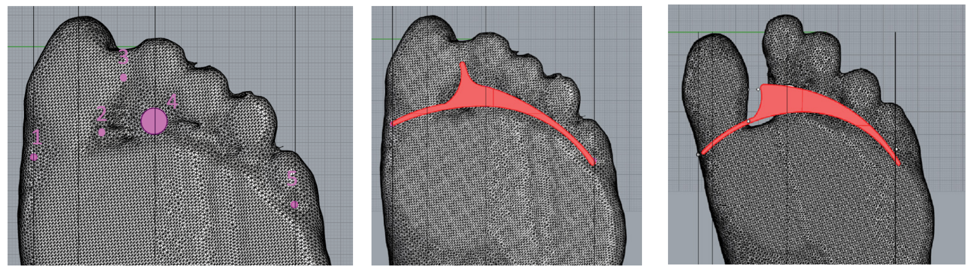
On observing the print of Prototype 2a, the Toe hold area was too acute and the arch support was too narrow. The stransition between the zones was rough and the heel area did not provide enough support. These shortcomings were corrected and Prototype 2b was printed.



2. Toe hold

The Next prototype implemented the toe grip concept. Three zones were defined in the base inlay sole for personalisation: Toe hold, Arch support and heel. The arch support and heel were designed to be conformed to the shape of the foot.
The prototype also implemented holes on the surface of the inlay sole. The Gyroid is an open unit cell. Every point in the inside is connected to every other point inside. This provides high level of breathability. Adding holes in the shell surface ensures active ventilation during strides due to the compression and rarefaction of the inlay sole.

Elements from Morphological Chart:
1.ii , 2.iii, 3.ii, 4.ii, 4.iii, 5.i, 5.iii

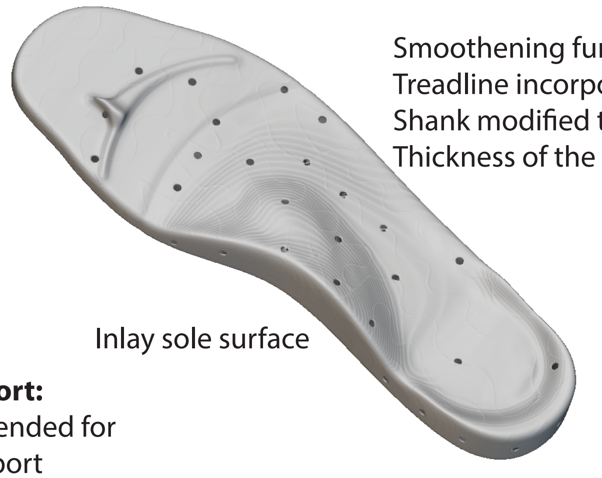


5 Point Measurement | YK | JS

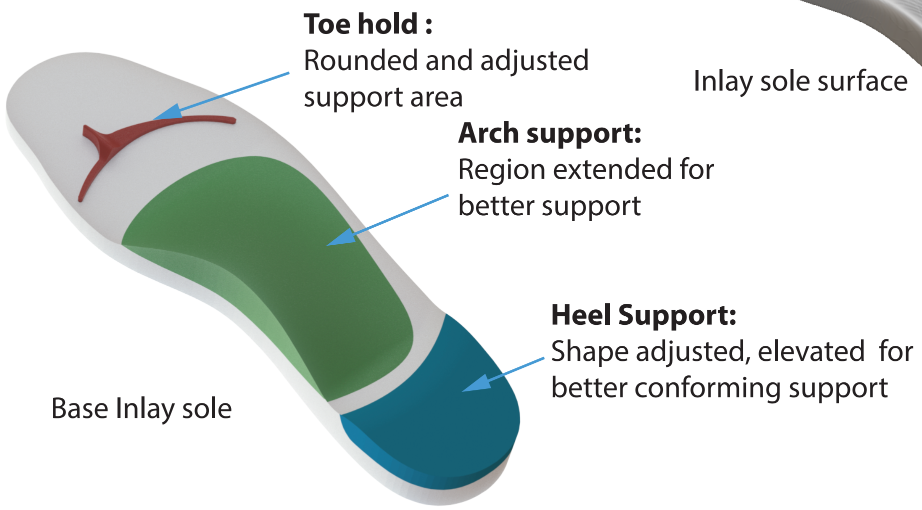
A fully conforming forefoot region restricts the freedom of movement of the toes. However an explorative qualitative study by Anderson et al. (2020) shows that workers prefer more grip inside the shoe. Toe grip zone is designed using parameters accommodates proper fitting. Here, Five points of measurement was taken from the scan of the foot in the loaded condition to define the contour of the toe grip.

Prototype 2B

Smoothening function adjusted
Treadline incorporated as a field addition
Shank modified to follow treadline
Thickness of the gyroid increased to 1mm for better meshing.



Inlay sole surface



Base Inlay sole

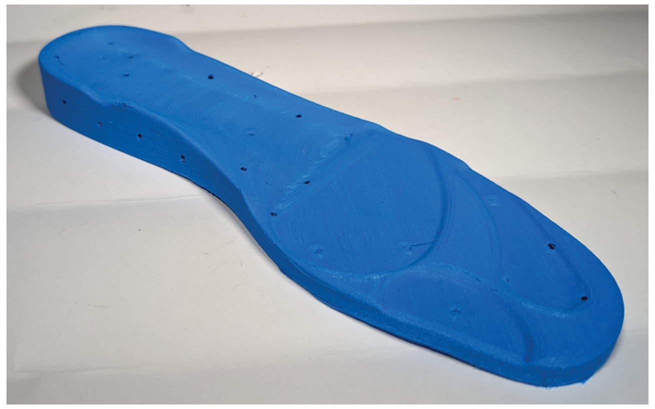
Material: TPU 95A

Prototype 2b was reviewed with the user. The toe hold was identified to provide grip but was still too prominent and caused uncomfort. A lack of side support in the inlay sole to guide the forefoot and toes was identified. It was also noted that varying the thickness of the lattice structure caused areas with increased localised hardness which caused discomfort.

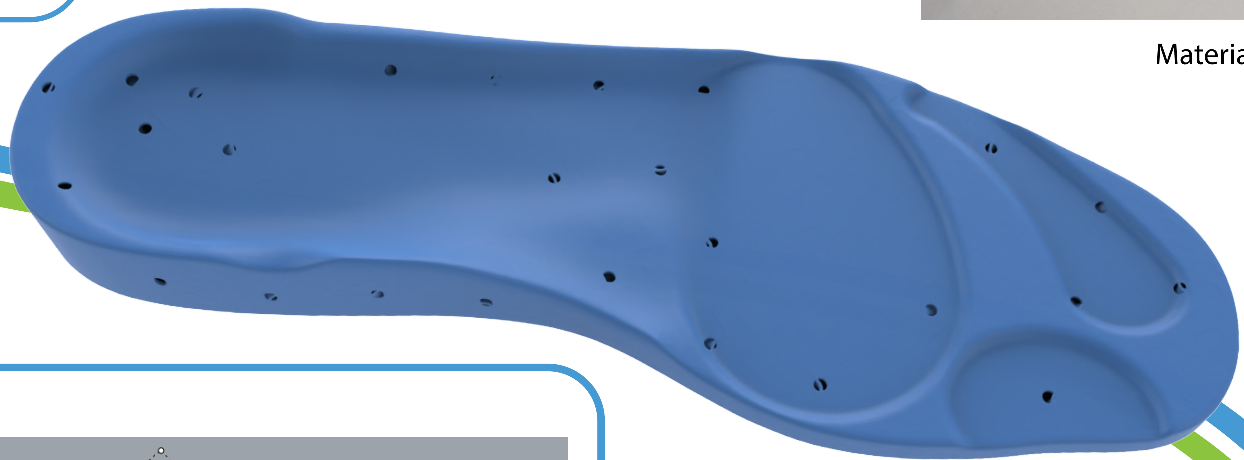
3. Toe grip

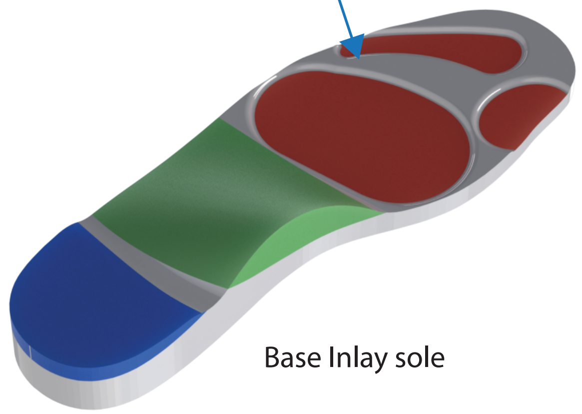
After understanding the limitations of the previous design, for The next prototype, a new concept of a toe grip design is tried out. Here, a Simplified skeletal representation of the plantar region is extracted from the 3D scans and the forefoot is customised . This design does not have protruding features, and provides side support for the metatarsal and toe areas. For the internal structure, the thickness of the lattice was kept constant and the only the cell size was varied

Elements from Morphological Chart:
1.ii , 2.iii, 3.ii, 4.ii, 5.i, 5.iii

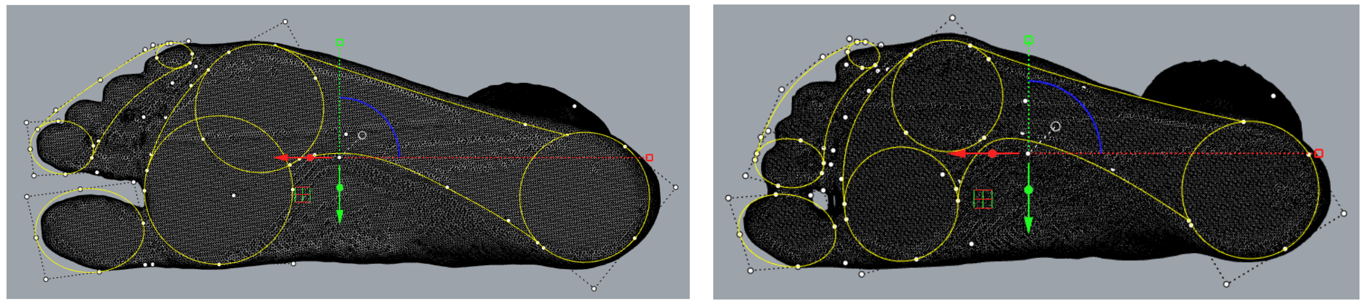


Material: TPU 95A





Simplified footprint representation



JS YK

Upon observation of Prototype 3, The top surface the features were found to be too hard and strongly defined. Testing with the users showed that the support features in the forefoot were too subtle to be felt.

4. Soft Material

These prototypes were printed in TPU with lower shore hardness values. This prototype has smaller unit cell dimensions and this allows for a higher degree of localised customisation and pressure distribution.

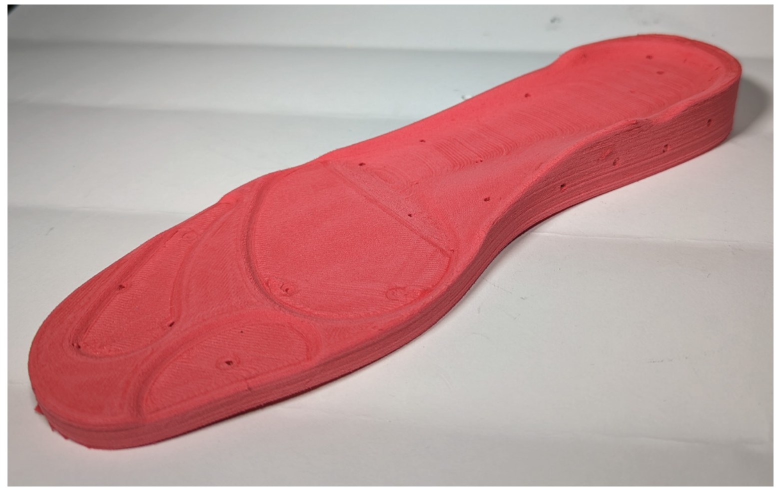
Elements from Morphological Chart:
1.ii ,2.ii, 2.iii, 3.ii, 4.ii, 5.i, 5.ii, 5.iii

Prototype 4A

Material: TPU 82A

Prototype 4A with TPU 82A was very difficult to print and had very poor print quality and was deemed not feasible for production. Prototoype 4B with varioshore had good finish and desirable mechanical properties.

Prototype 4B

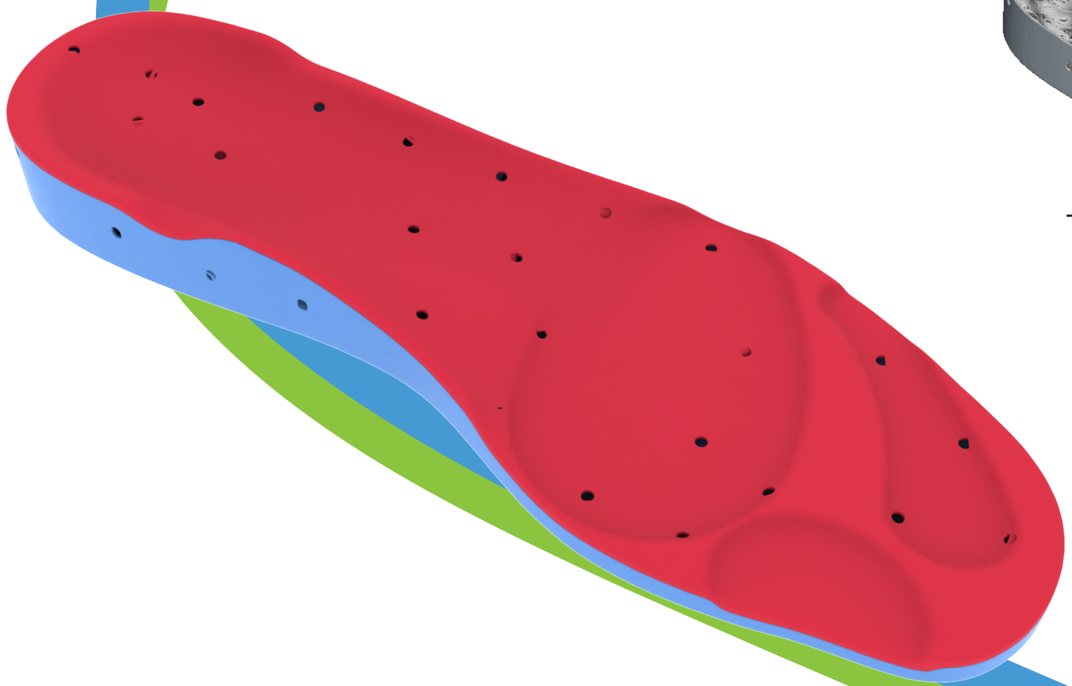


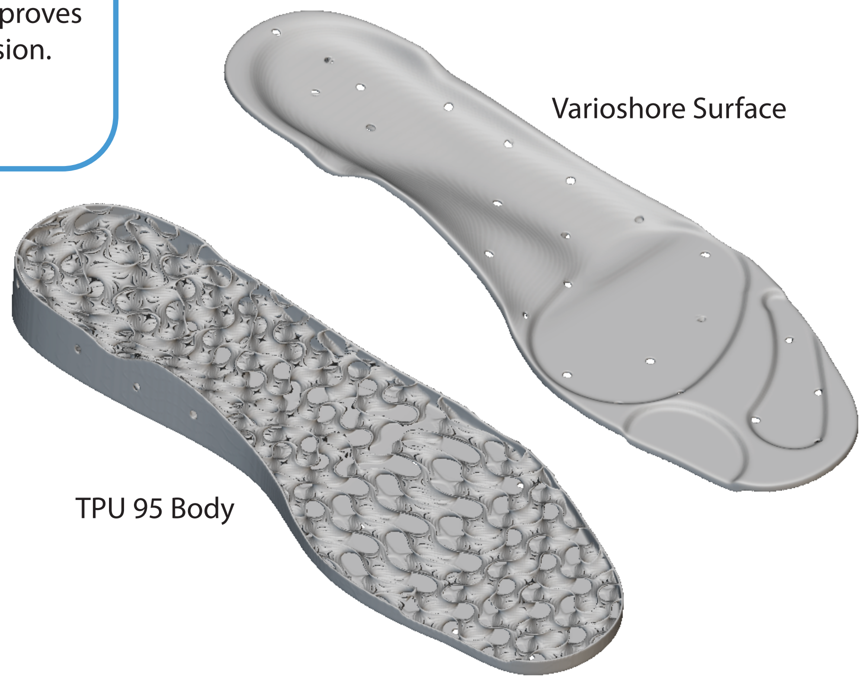
Material: Varioshore

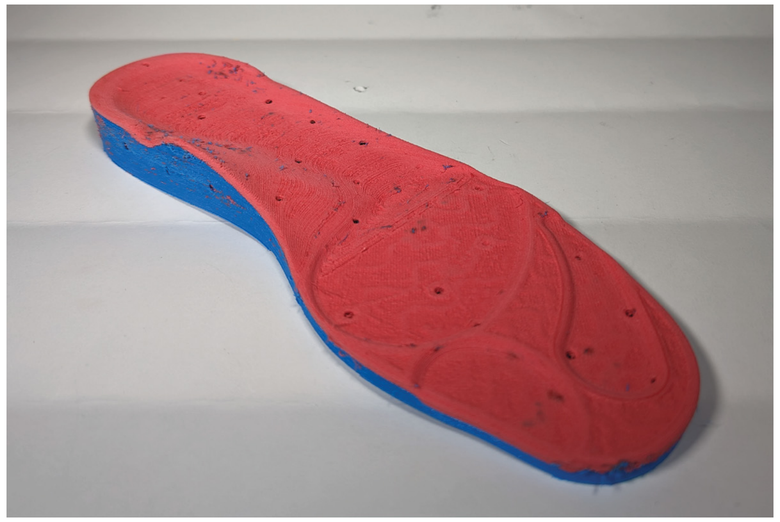
5. Multi-material

Another prototype where the bulk of the inlay sole is printed in TPU 95A and the top 3mm of the surface is printed with softer varioshore. The softer top surface improves cushioning and comfort for the user. This prototype uses dual mterial extrusion.

Elements from Morphological Chart:
1.i, 1.ii ,2.ii, 2.iii, 3.ii, 4.ii, 5.i, 5.iii







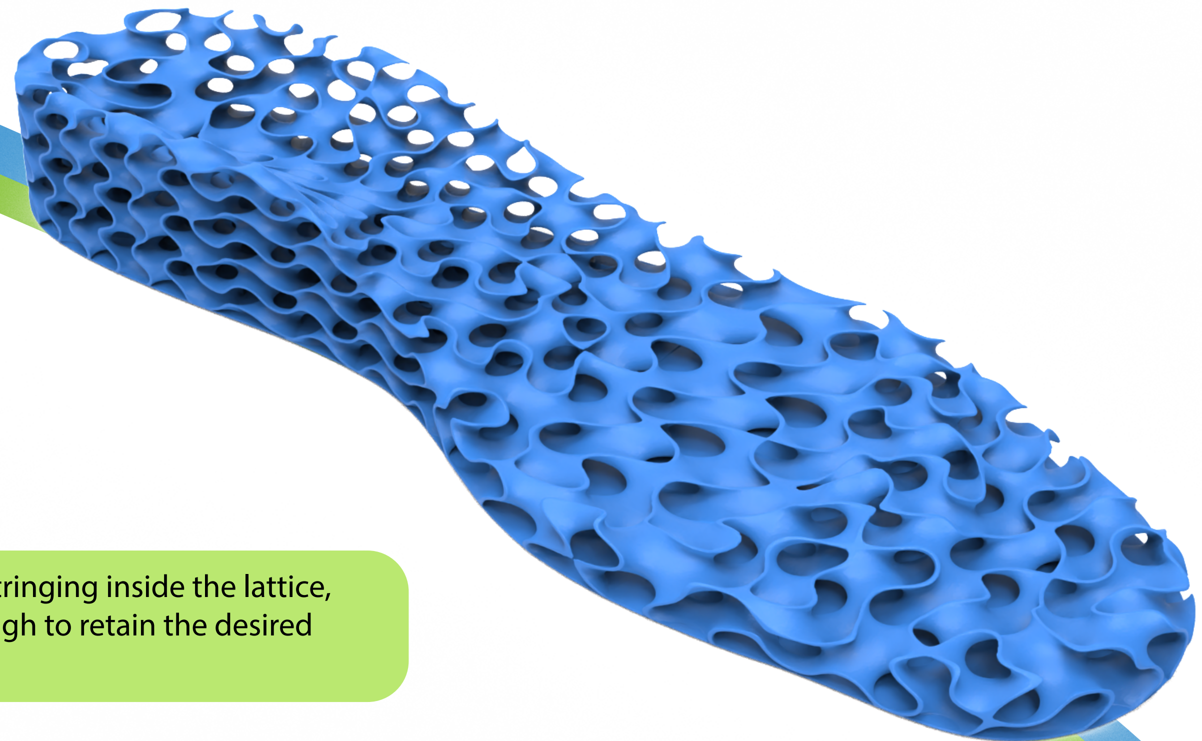
Material: Varioshore and TPU 95A

Prototype 5 did not appear to provide any significant benefit over Prototype 4B. Further, mixing material, makes it more difficult for recycling.

6. Open Prototype

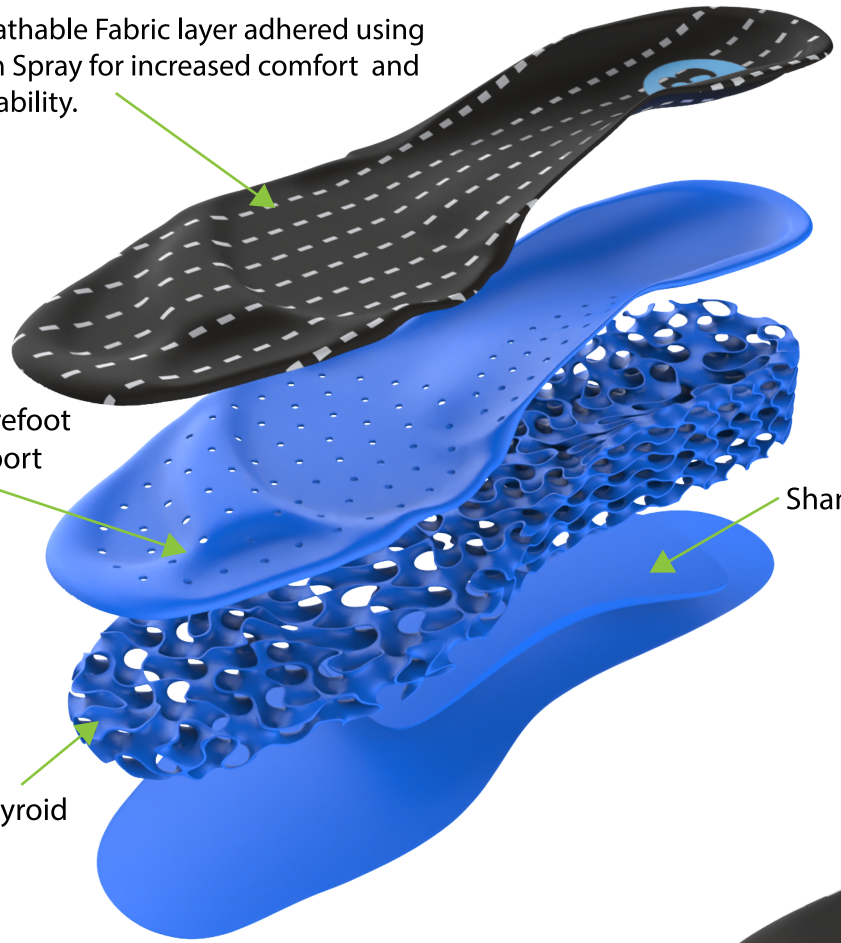
The open prototype was printed without walls to showcase and observe the internal structure and the quality of the print of the inlay sole.

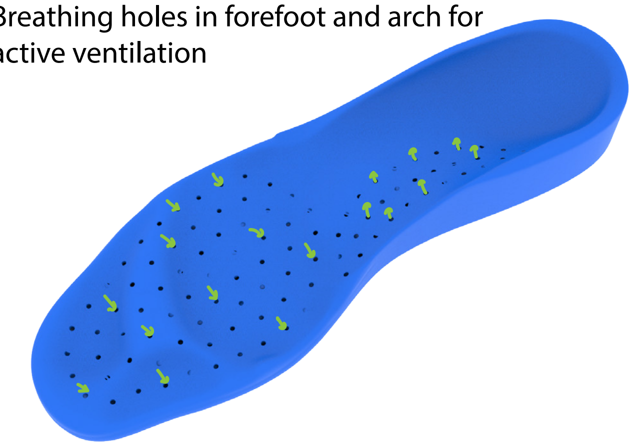
1.ii , 2.iii, 3.ii, 4.ii, 5.i, 5.iii
Elements from Morphological Chart:

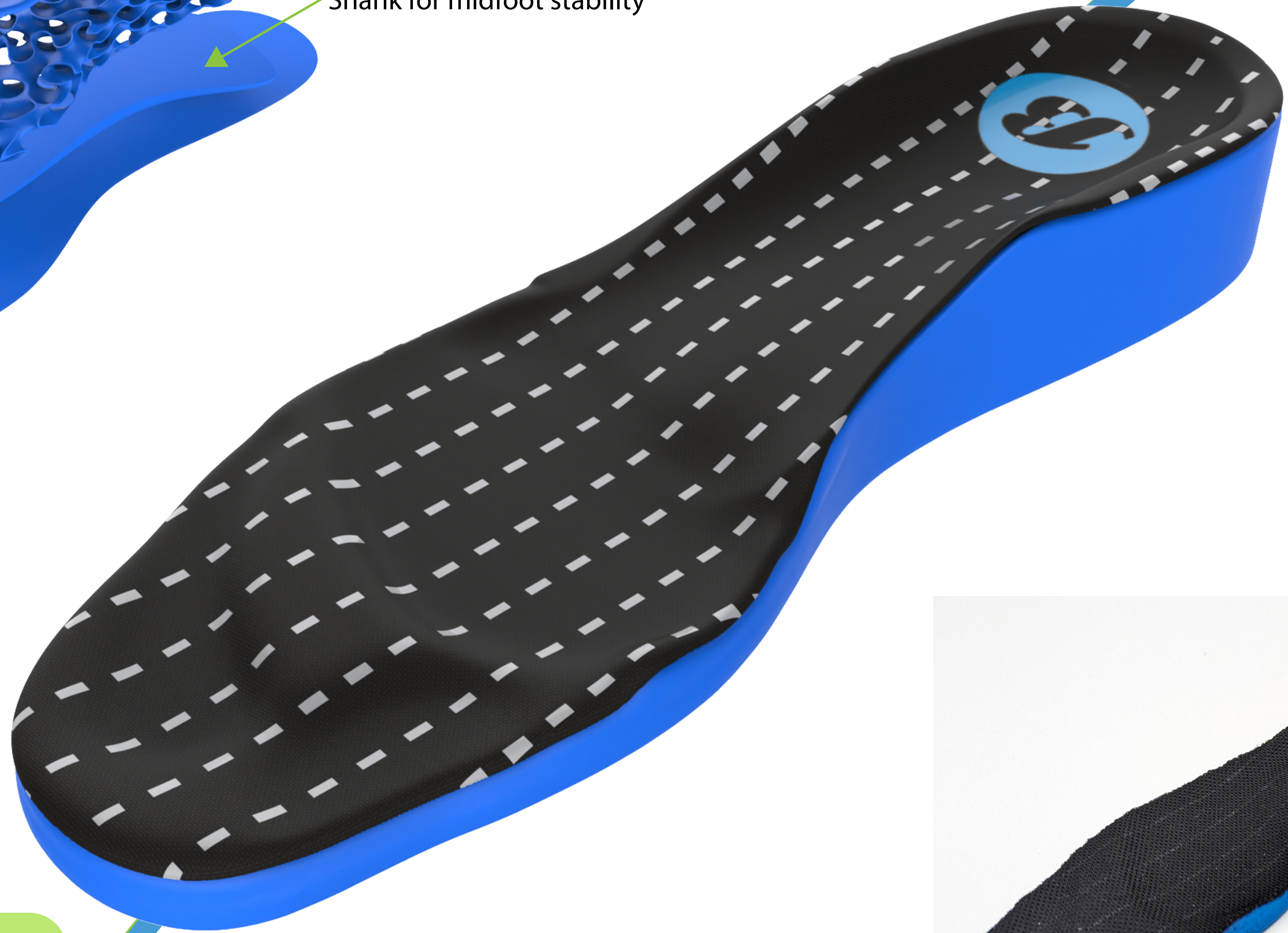


Material: Varioshore

Prototype 6 showed some amount of stringing inside the lattice, however, the print quality is good enough to retain the desired properties







Detailed testing of this prototype was carried out which is explained in the next section

7. Final Prototype

This is the final prototype that incorporates all the learnings from the previous prototypes. The design features a smooth forefoot area incorporating both the Toe grip and toe hold designs. Extra side support was given in the forefoot and the heel to properly locate the foot. The breathing holes were redefined to the arch and forefoot area based on input from Bata, considering the areas that require the most ventilation and support. A fabric layer was adhered on top which enhances comfort and durability.

Elements from Morphological Chart:
1.ii, 2.i , 2.iii, 3.ii, 4.i, 4.ii, 4.iii, 5.i, 5.ii, 5.iii

Material: Varioshore
3D Printed inlay sole without fabric

Inlay sole with fabric adhered

8. Multijet fusion Prototype

A multijet fusion print of the envisioned futuire inlay sole was done. This prototype has a smaller unit cell size (between 7mmX7mmX7mm to 15mmX15mmX15mm) and smaller wall thickness (0.7mm), which allows for finer resolution for controlling the response provided by the inlay sole. This demonstrates to a better extent, the possibilities of making use of lattice struictres to distribute plantar pressure

Elements from Morphological Chart:
1.ii, 2.iii, 3.ii, 4.ii, 4.iii, 5.i, 5.iii

Material : Ultrasint TPU 90A

Open sides to demonstrate Internal Structure

The different production process and material resulted in a stiffer inlay sole than expected. However this prototype clearly portrays the localized customization of pressure response possible with the field driven lattice approach employed in the project.

4.3. Workflow

This section, shows the workflow involved in creating the inlay sole in detail. The designing of this process is one of the main outcomes of the project.

Preparation

Base Inlay sole:
A base inlay sole based on the dimensions defined by the shoe design is created in a CAD program (Solidworks is used in the project). The Base inlay sole has a high arch and heel area which will be personalized at a later point based on the collected data from the measurements. The sole has a curved top surface to accommodate a comfortable fit of the foot. The base inlay sole is shown in Figure 49.

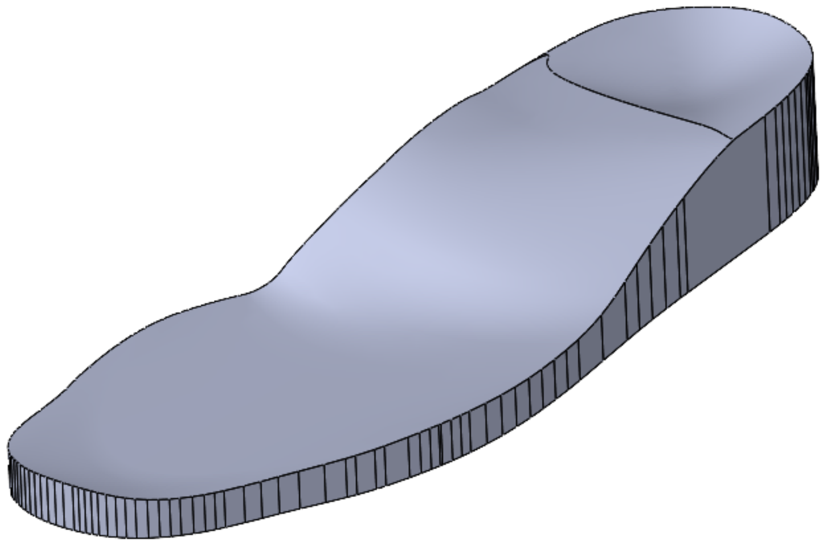


Figure 49. Base Inlay sole

Shank:
A separate CAD model of the inbuilt shank is created which provides midfoot stability and torsional stiffness to the inlay sole.

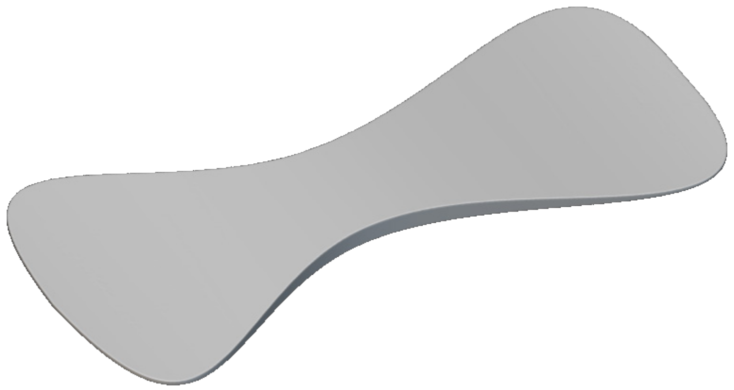


Figure 50. Shank

Pressure Data extraction
From the data recorded during gait, 20 strides in the middle are extracted and averaged into a single stride. The peak pressure at each sensel during the stride is recorded and this is used as the data for which the correction is done.

Conversion of Pressure data to point map
A python script (see Appendix 3) is used to covert the pressure data into a X, Y Z point data in a format supported by Ntop.

Extraction of Footprints
A simplified footprint is extracted from the 3D scans of the foot in the loaded state. The proposed footprint can be defined by the following features: Heel circle, Metatarsal Circles, Big toe and toe contours See Fig 51. This footprint is proposed to encompass important features that this allows to visualize the position of important features of the foot on the inlay sole.

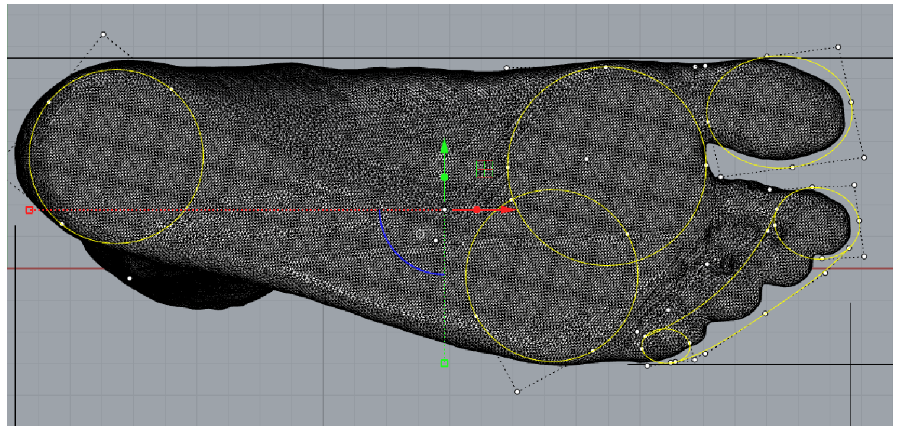


Figure 51. Simplified Footprint

Incorporating forefoot features in the base inlay sole
The simplified footprint is used as a basis for defining the features. The position of the toes are adjusted to fit within the inlay sole. The forefoot features are defined by the areas of recess and areas of support. Support is added to areas to help in the positioning and ensuring snug fit of the forefoot.

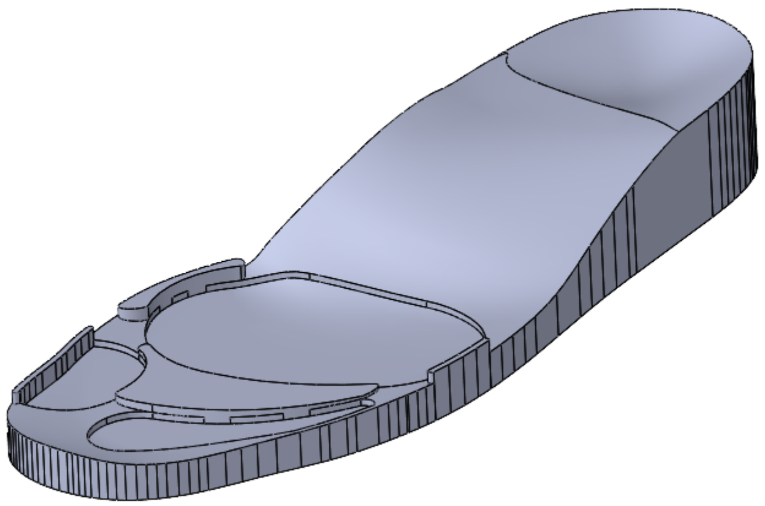


Figure 52. Inlay sole with Forefoot Features

Further processing is done in Ntop. Ntop works using Blocks which allows for design automation as replacing the inputs automatically generates new output. Hence personalisation can be easily done for different users given that the inputs are homogenous.

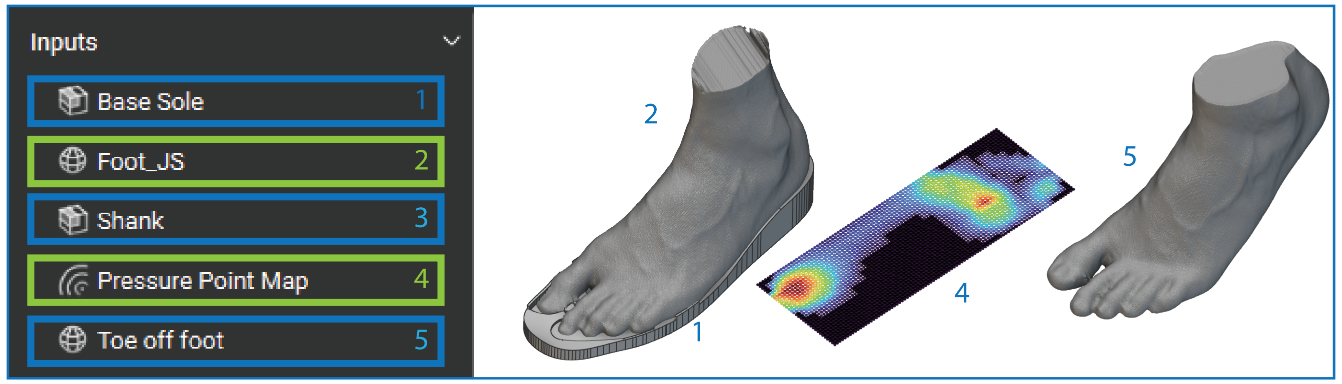


Figure 54. Input Blocks

Inputs:

1. The base inlay sole with forefoot features
2. The 3D scan of the foot in unloaded conditions
3. The shank
4. The Point map
5. The 3D scan of the foot in toe off condition

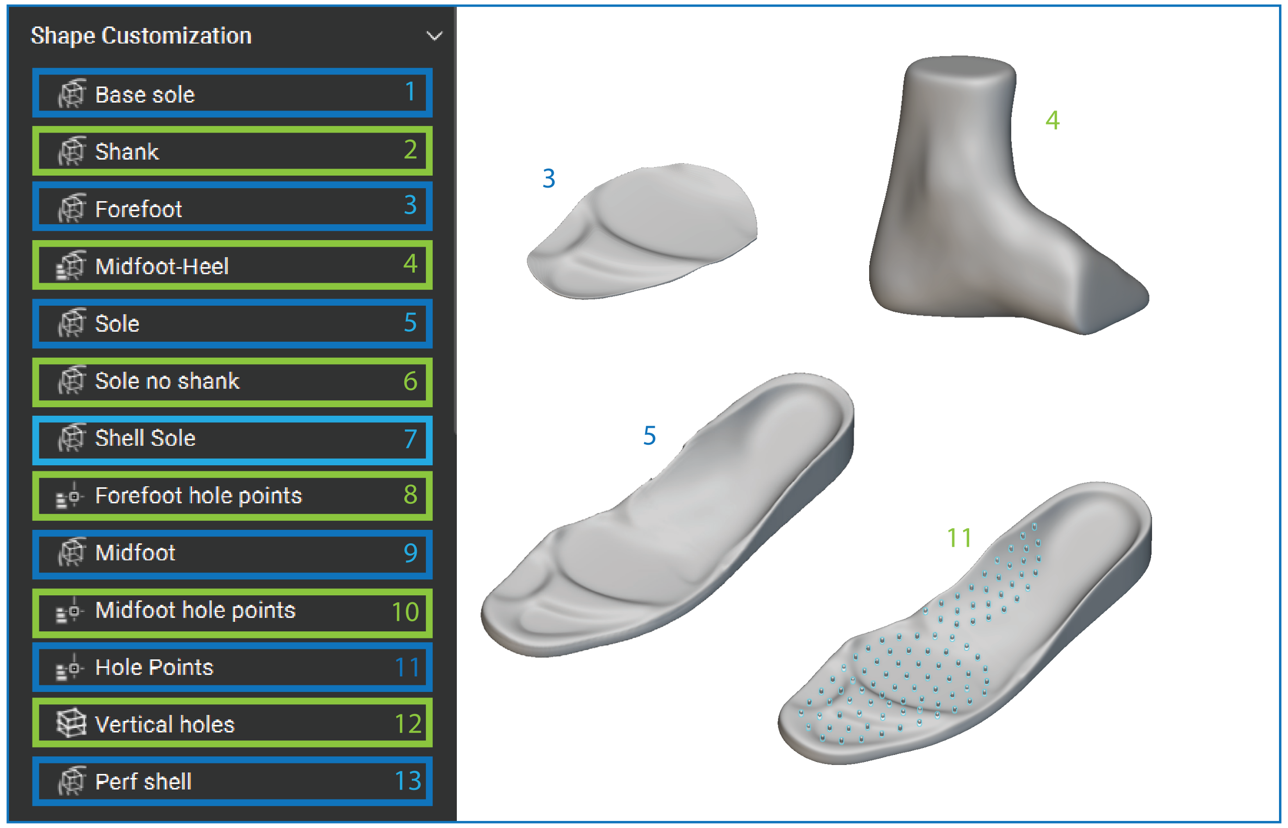


Figure 53. Shape customization blocks

Shape Customization

1. Base inlay sole converted to an implicit body for processing in nTop
2. Shank converted to an implicit body for processing in nTop
3. The forefoot area of the inlay sole is isolated and a smoothening function with is applied to generate a smooth surface incorporating the features desined.
4. Since the shape of the arch can vary a lot between individuals, to provide optimal support, a simplified model of the 3D scan which includes the arch and heel is used. Iterations identified the model in the unloaded condition to provide optimal support.. A smoothening function with n iteration is performed to remove minor details.
5. The shape of the inlay sole is defined by subtracting the midfoot and heel model from the base inlay sole and incorporating the forefoot topology.
6. The Shank Section in subtracted from the sole to define the functional volume.
7. A shell of thickness 0.6mm is generated to define the outer surface of the inlay sole.
8. The points for holes in the forefoot area are defined based on the information obtained from Bata.
9. The points for holes in the midfoot area are defined based on the information obtained from Bata.
10. The concatenation of all the points for holes.
11. Defining the size of the holes.
12. The perforated shell model with the holes subtracted from the shell.

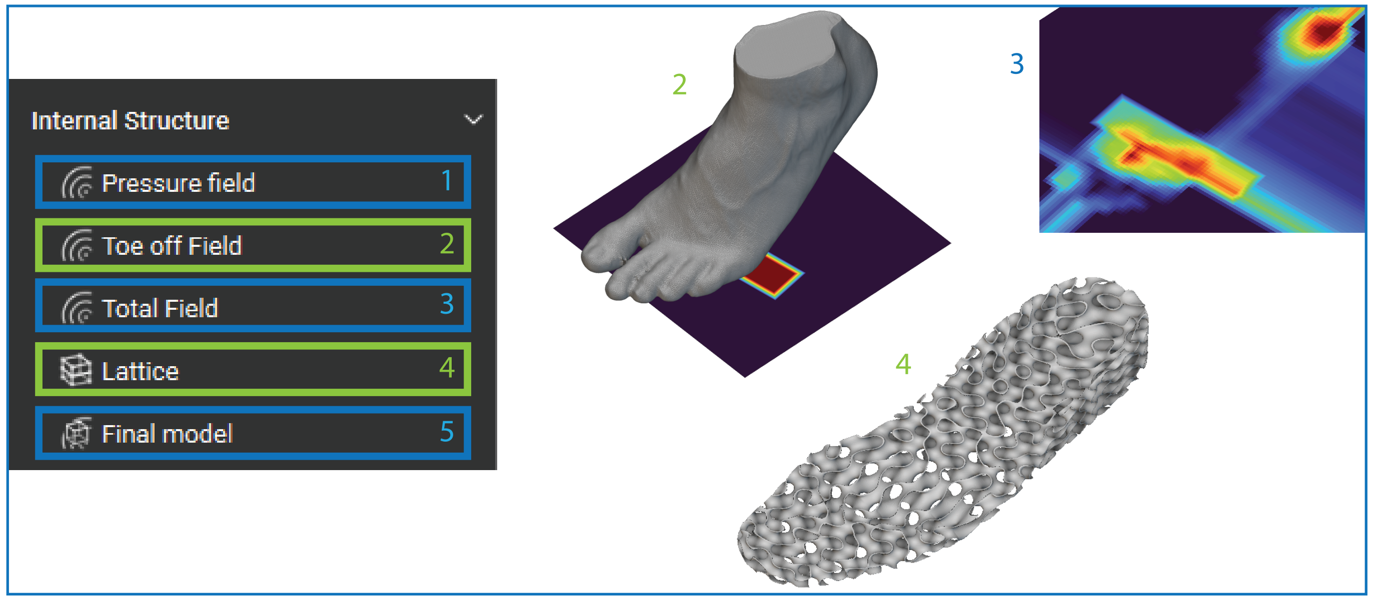


Figure 55. Internal Structure Blocks

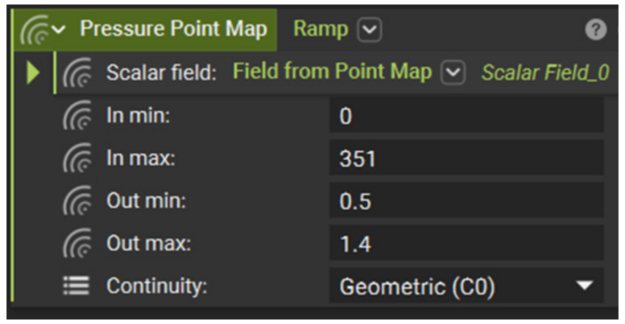


Figure 56. Pressure Remap

Internal Structure

1. The Point map is converted to a field, aligned with the sole and the values remapped as shown.
2. The treadline is determined from the toe off 3D model and a field is added in the area to enable easier bending during toe off.
3. A total field is generated by adding both the pressure and toe off field.
4. A rectangular cell map is created with cell size 20X20X10 The cell height is kept constant at 10mm so that one full cell exists in the Forefoot area of the inlay sole. The gyroid unit cell is used and once the scaling is applied, the cell size vary from 10mmX10mmX10mm to 34mmX34mmX10mm. The Lattice is trimmed to the inlay sole.

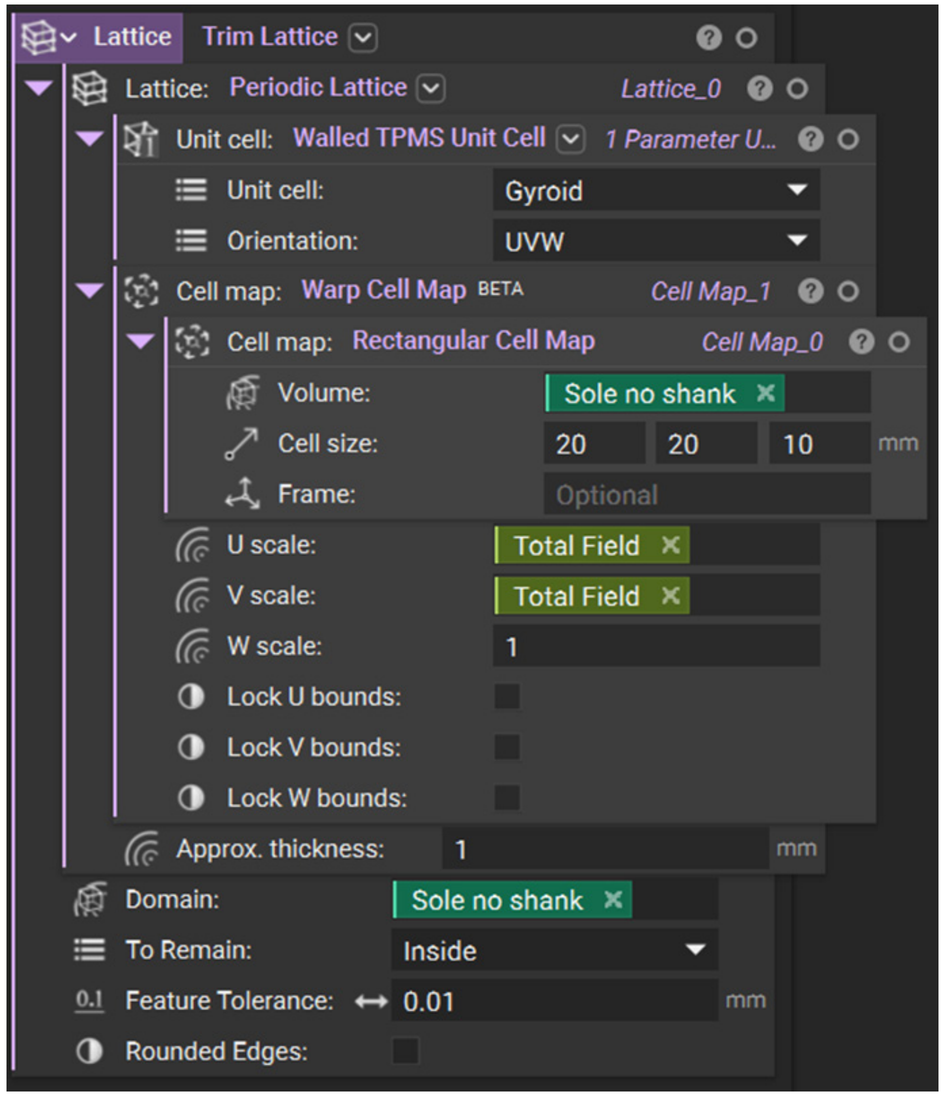


Figure 57. Lattice

5. The Final Model is Generated by combining the perforated shell, the lattice and the shank.

Meshing and Slicing

1. The Final Model is converted to a mesh with the following settings
2. The mesh is exported as a 3mf file.
3. The exported 3mf file is sliced in Cura.

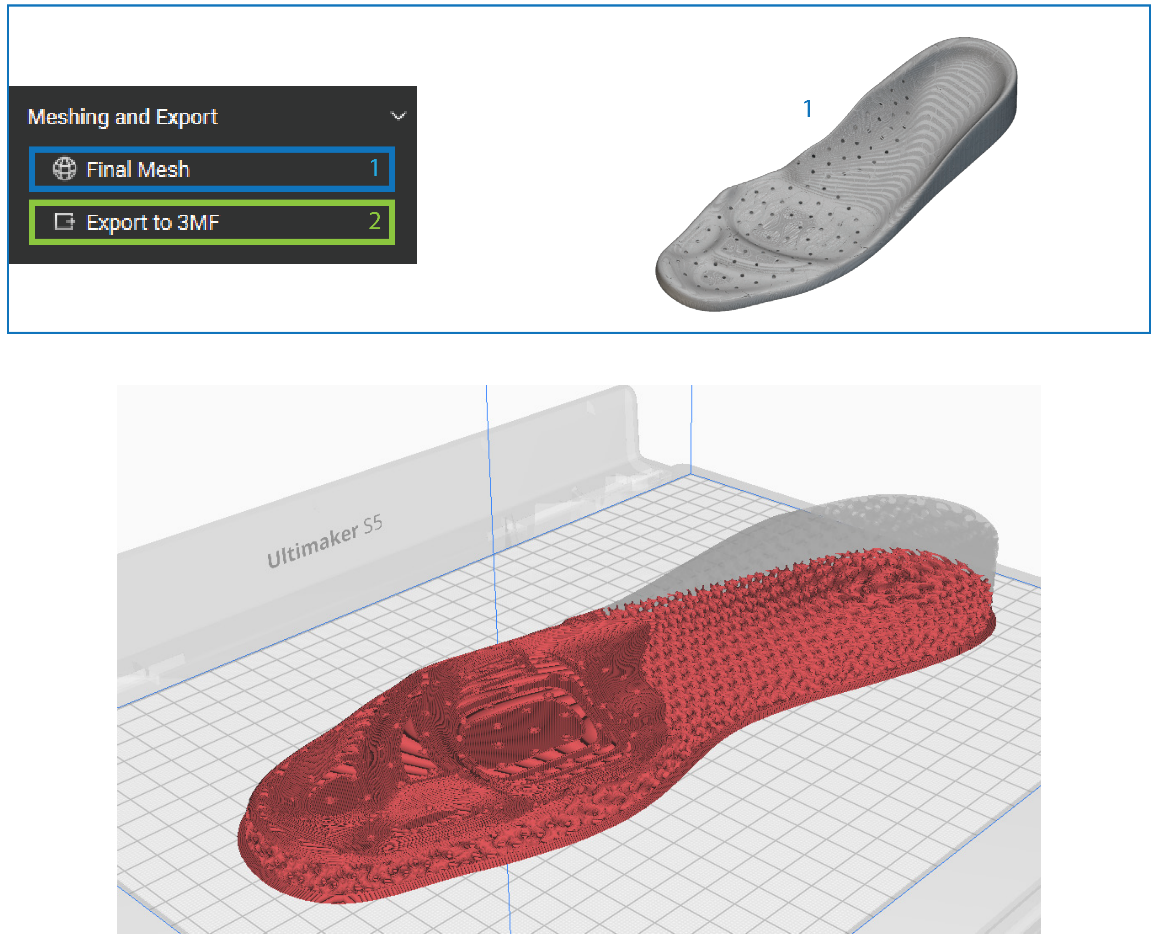


Figure 58. Meshing and Slicing

5. Validation

The final solution is validated through feedback from users and mechanical testing. Additionally, a cost analysis is conducted to assess the investment necessary for commercializing the solution.

5.1. User Testing

In this section, the final prototype of the personalized inlay sole is validated with the users

Construction of Shell Shoe

As the inlay soles are thicker than conventional inlay soles, for testing it with the users, a pair of shoes with extra space for housing or “shell shoes” were designed and prototyped. The shoe consists of an outsole cemented to the upper with a representative toe cap. The outsole is made from TPU and is 3D printed using FDM. The design is printed flat, and the front is curved while cementing to the upper. The bottom of the Outsole (which was in contact with the build plate) is flat without any wear pattern, but the surface is sanded to increase the grip. The new toecap is a modification on the conventional toe cap with the height increased 5mm. For the prototype, the toe cap is 3D printed using PLA which acts as a placeholder.
An addition was also 3D printed using PLA and glued onto the conventional last of the shoes from Bata to allow for the cementing of the upper to the outsole. The construction of the shell shoe is shown in Figure. 59.

Figure 59. Shell Shoe construction

The Comparative test

Research Question:
The objective of the study was to conduct a comparative analysis of the personalized inlay sole.

Testing
The test was conducted with 3 types of samples:

A. **Standard Inlay sole from Bata:** A standard inlay sole provided with Bata safety shoes. A filler was added to match the height to the new inlay soles.

Figure 60. Standard inlay sole

B. **Non personalized Inlay sole:** A 3D printed inlay sole without any personalized customization. The sample was FDM 3D printed using Varioshore.A textile layer was adhered to the top using Lijm spray.

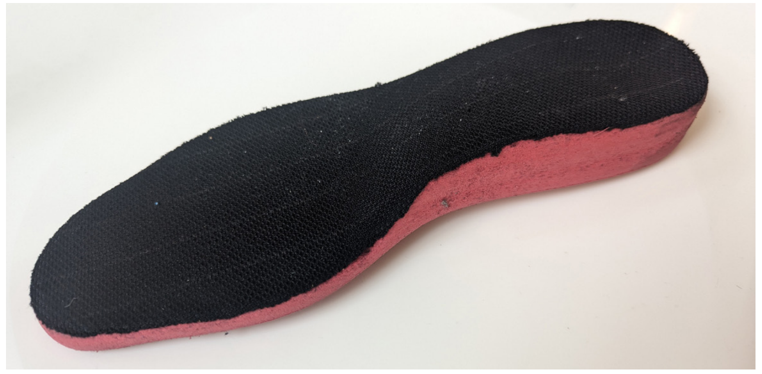


Figure 61. Non personalized inlay sole prototype

Figure 62. Non personalized inlay sole CAD Model

C. **Personalised Inlay sole prototypes:** The final personalized prototypes. One pair was FDM 3D printed for each of the two participants using Varioshore. A textile layer was adhered to the top using Lijm spray.

Figure 63. Personalized inlay sole prototype

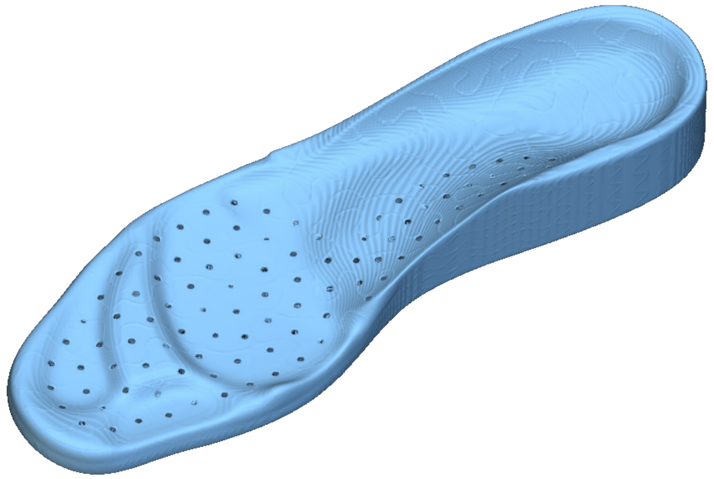


Figure 64. Personalized inlay sole CAD Model

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Test Part 1: Subjective testing

The objective of this test was to gather subjective feedback on the samples without revealing any details and biasing to the users. The following steps were followed:

The participant was given the opportunity to try on the shoe fitted with each sample A,B and C.
The details of the samples were not disclosed to the users during the testing phase.
Participants were instructed to wear the shoe and walk around to get comfortable with it for a duration of 2 minutes.
After the 2-minute period, participants were presented with an open ended questionnaire/ interview containing relevant questions about their experience with the shoe.
The responses provided by the users in the questionnaire were recorded as a for further analysis and evaluation.

Figure 65. Testing of the samples

<u>**Questionnaire:**</u>

The following questions were presented to the participant. The participant was asked to rate each feature on a 10 point rating scale and their open feedback on each was recorded.

1. How is the comfort while walking?
2. How is the comfort while standing still?
3. How is the cushioning in Heel?
4. How is the Midfoot and Arch support?
5. How is the Forefoot fit?
6. Any comments on the Aesthetics?

Test Part 2: Plantar Pressure Test

The purpose of this test was to evaluate the plantar pressure distribution of each prototype using the Xsensor pressure sensing insole. The following steps were followed:

The shoe was fitted with each of the prototypes A, B and C along with the Xsensor insole.
They were instructed to walk a distance of 34 meters at their normal pace.
The Xsensor pressure sensing insole recorded the plantar pressure distribution during the entire walking distance.
Twenty steps in the middle were isolated and averaged out to create an averaged stride.
The data from this stride was compared between the different prototypes.

Results

Part 1

The ratings provided by the participants are shown in Table 6.

	JS			NB		
	A	B	C	A	B	C
Comfort while Walking	4	5	9	6	8	9
Comfort while Standing	4	5	7	7	9	9
Cushioning in the heel	3	8	9	8	10	10
Midfoot/Arch Support	1	1	8	6	6	9
Forefoot fit	4	7	9	7	7	8

Table 6. Rating from the participants

The important findings from the interview are listed below:

- Consistently the personalized inlay sole was rated as most comfortable even though the test was conducted blindly.
- The increased Cushioning response provided at the heel contributes to comfort while walking.
- The lack of Arch support in the standard inlay sole was noticeable.
- The arch support in the non-personalized sole was too high and did not provide comfortable cushioning.
- The Toe grip was identified to be unique compared to normal shoes but comfortable as it was perceived to provide a snug fit near the joint of the toes while providing more freedom for the toe tips.
- The side support walls in the forefoot area do not stand out, but the forefoot comfortably fits in the shoe.
- One participant did not care about the aesthetics as it is hidden in the shoe and prioritized comfort. The other person liked the features that showed personalization that made it unique and felt it would look great with a pattern on the fabric and a logo.

Part 2

To perform a comparison between the pressure data for each sample, 20 strides from the middle are isolated and averaged into a single stride. The peak pressures recorded by each sensel during this averaged stride is mapped. This is shown in Figure 66. The plantar foot is also divided into regions as shown in Figure 67. The peak and average pressures observed in each region of these regions of the foot is tabulated in Table 7.

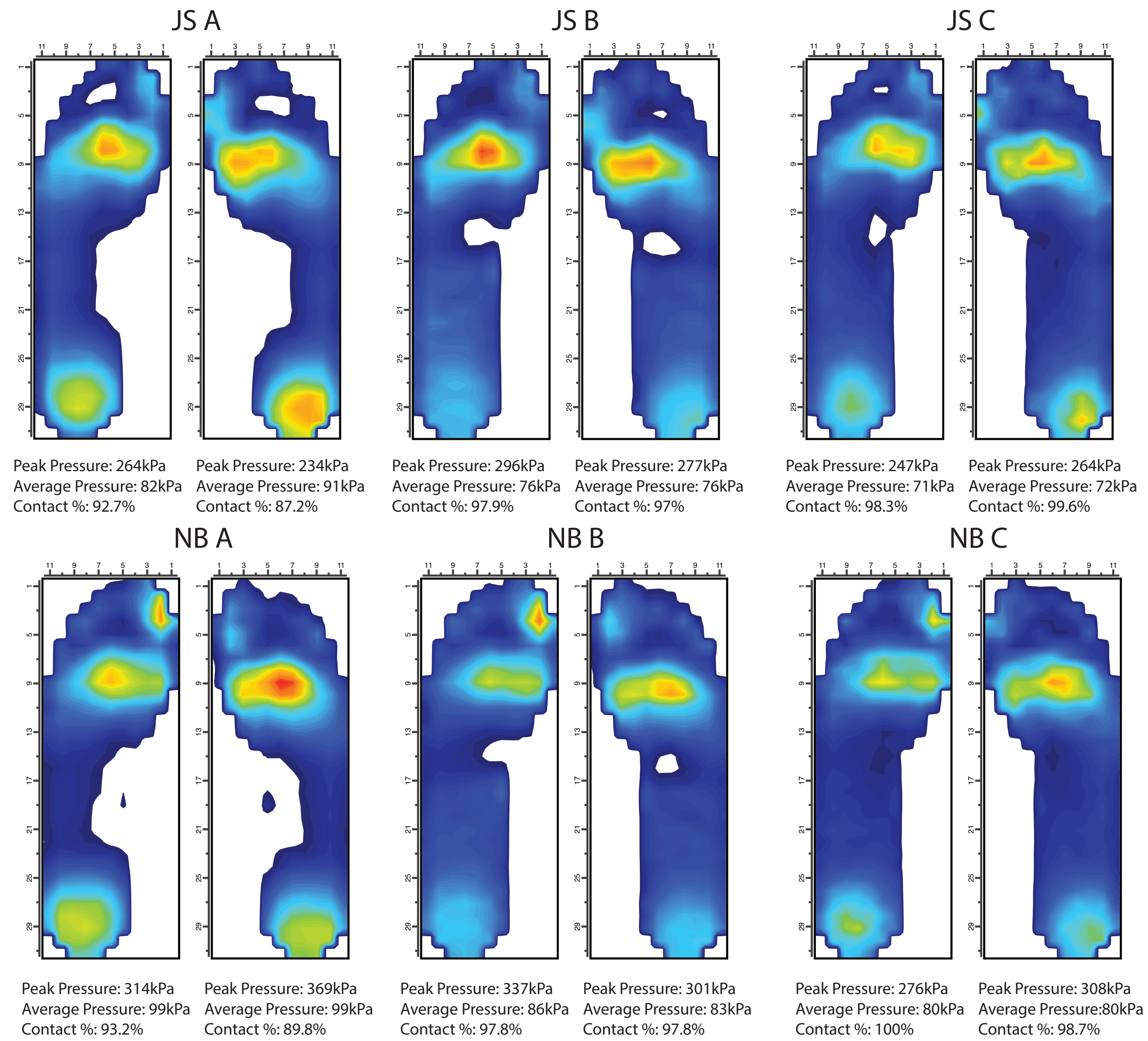

Figure 66. Peak pressures during the averaged stride

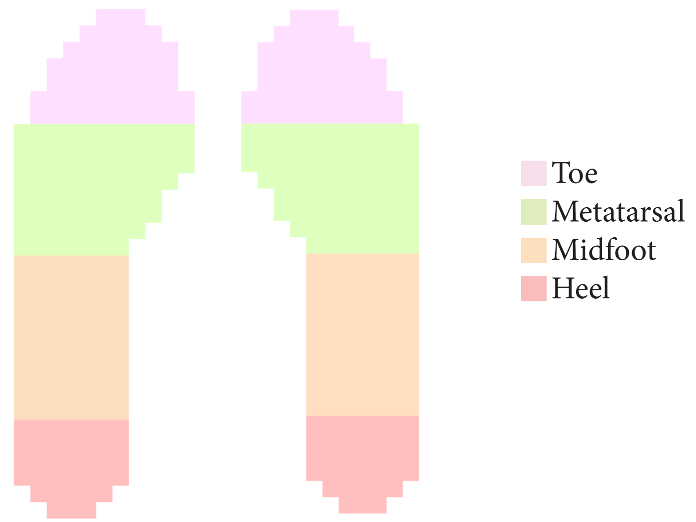

Figure 67. Sections of the foot

			kPa	A	B	C
JS	Left	Foot	Avg	82.73	76.32	71.3
			Peak	264.56	295.94	247.4
		Heel	Avg	142.6	102.23	118.2
			Peak	216.05	128.12	178.67
		Midfoot	Avg	38.98	53.54	36.63
			Peak	106.33	85.11	88.96
		Metatarsal	Avg	89.11	94.76	74.04
			Peak	264.56	295.94	247.4
		Toes	Avg	79.32	63.49	81.16
			Peak	239.81	235.23	239.84
	Contact %			92.77	97.87	98.3
	Right	Foot	Avg	91.06	75.81	72.46
			Peak	253.84	276.63	263.7
		Heel	Avg	165.03	102.1	118.34
			Peak	251.9	164.85	244.2
		Midfoot	Avg	32.71	43.49	29.79
			Peak	93.16	79.32	63.53
		Metatarsal	Avg	110.33	111.18	99.67
			Peak	253.84	276.63	263.7
		Toes	Avg	60.51	48.95	55.52
			Peak	183.73	151.44	183.79
	Contact %			87.23	97.02	99.57
			kPa	A	B	C
NB	Left	Foot	Avg	99.22	86.1	80.09
			Peak	313.93	336.9	275.76
		Heel	Avg	188.1	124.31	140.17
			Peak	256.7	161.03	238
		Midfoot	Avg	29.74	51.98	31.76
			Peak	112.77	97.44	87.96
		Metatarsal	Avg	111.72	94.9	92.59
			Peak	290.36	253.14	269.7
		Toes	Avg	88.44	88.64	80.86
			Peak	313.93	336.9	275.76
	Contact %			93.19	97.87	100
	Right	Foot	Avg	98.79	82.96	79.71
			Peak	369.27	301.16	308.14
		Heel	Avg	168.22	112.84	126.86
			Peak	243.36	168.87	211.18
		Midfoot	Avg	25.73	41.72	30.33
			Peak	81.36	75.65	69.89
		Metatarsal	Avg	141.37	124.54	121.42
			Peak	369.27	301.16	308.14
		Toes	Avg	59.76	58.13	50.38
			Peak	165.69	185.3	153.95
	Contact %			89.79	97.87	98.72

Table 7. Pressure Readings in defferent sections of the foot

Conclusion:

- The personalized inlay sole effectively increased the contact area between the sole and the foot. As a result, the average pressure experienced by the foot was notably reduced compared to other inlay sole types. This finding indicates that the personalized design offers better weight distribution and support during walking, leading to enhanced overall comfort.
- Despite the improvements achieved with the personalized inlay sole, the pressure test revealed that peak pressures still tend to occur in the forefoot area. The forefoot region experiences the highest impact during walking and requires additional cushioning to alleviate pressure points and enhance user comfort.
- The design of the personalized inlay sole succeeds in redistributing the pressure across the foot to some extent, promoting a more even pressure distribution, reducing the risk of foot-related discomfort, and supporting proper foot biomechanics. However, there remains an opportunity to improve pressure relief in the forefoot area further.

5.2. Compression Testing

A compression test is conducted to evaluate the difference in response in different areas of the forefoot, and the differences are compared.

Procedure

<u>Prototype 7:</u>

Four Different points in the forefoot are identified as shown in Figure 68. The field values of these points match the samples tested in Section 2.2 so a direct comparison can be made. An attachment was 3D printed from PLA for the Zwick testing machine to reduce the contact area to a circle of 10mm diameter to conduct the testing(Refer Figure 69. The other testing parameters are kept same as in Section 2.2

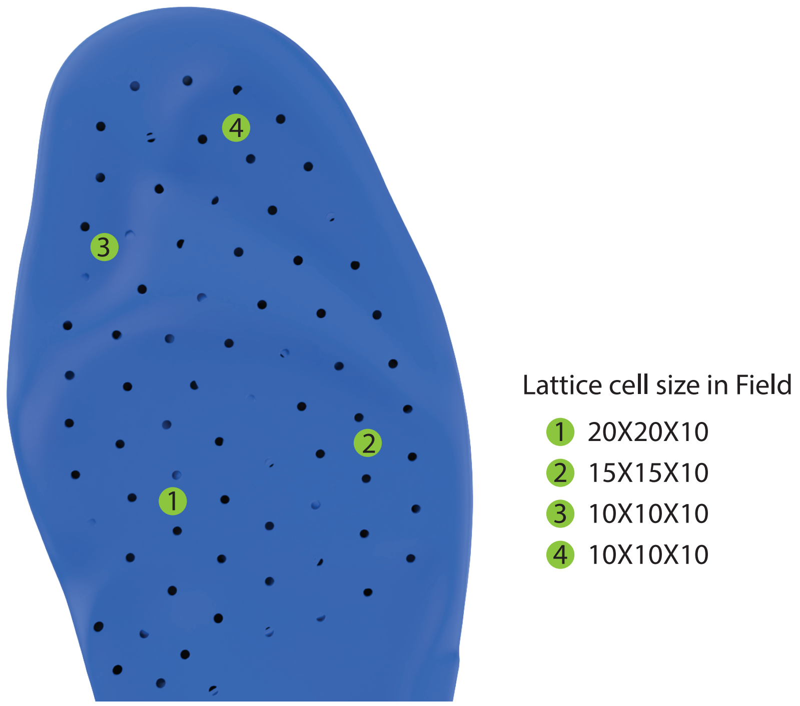

Figure 68. Points of compression testing

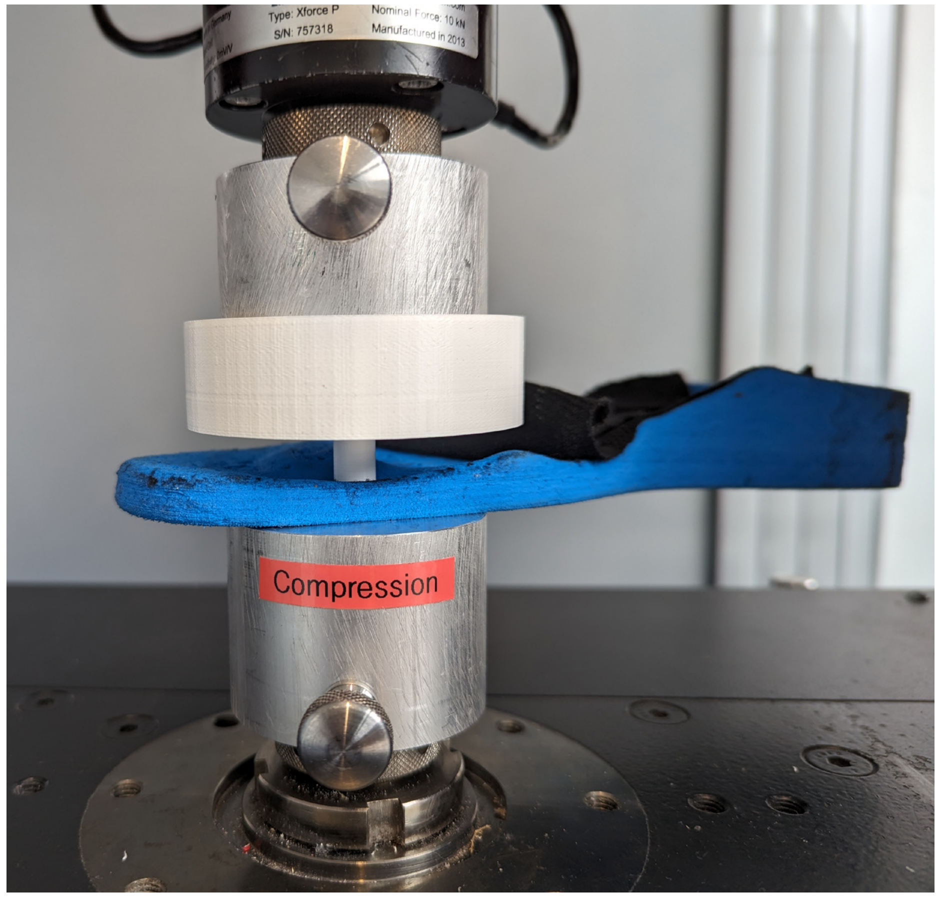

Figure 69. Compression testing setup

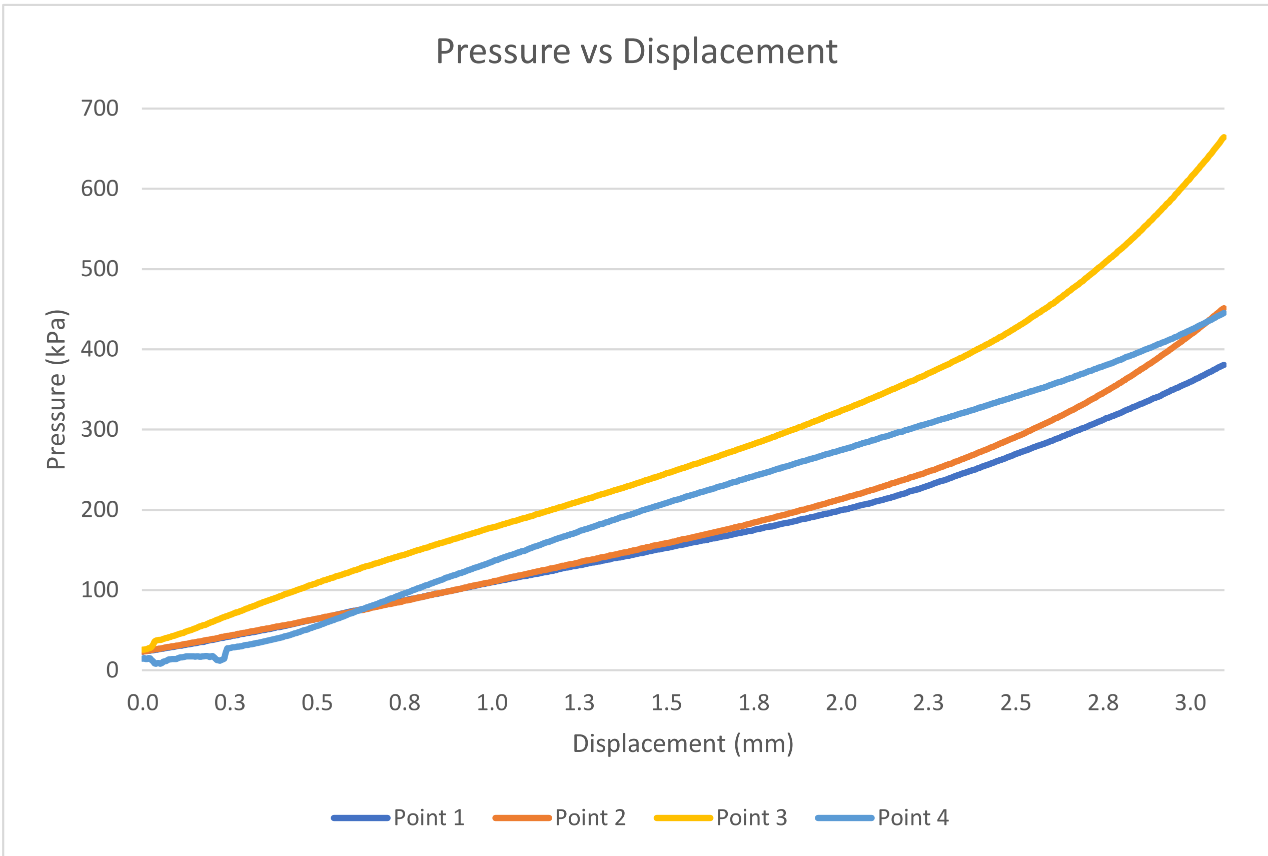

Figure 70. Pressure vs Displacement graph of prototype 7

Observations:

The Pressure vs. Displacement graph that was obtained from the testing is shown in Figure 70.

The MJF prototype

The same testing is also done in the Multijetfusion prototype (Prototype 8) which has a smaller cell size (between 7X7X7 and 15X15X15) and lower thickness (0.7mm) for the lattices.

Observations:

The Pressure vs. Displacement graph that was obtained from the testing is shown in Figure 71.

Conclusion

The conducted testing of Prototype 7 did not reveal the anticipated significant differences in response across the different points. This outcome is attributed to the limitations imposed by the large unit cell size. Somewhat better results were observed in the MJF prototype with smaller cell size and wall thickness. To attain finer control over the response, employing smaller unit cell sizes with reduced thickness is essential. Despite the feasibility of 3D printing such structures using FDM technology, a challenge emerged due to inadequate computer memory to generate the mesh with the necessary precision.

Overcoming this obstacle is conceivable in the near future through:

- Enhanced Computer Resources: An upgrade in computer memory or processing power could enable the generation of meshes with the required precision.
- Optimized Slicing and gcode Production: Exploring alternative slicing methods and techniques for generating gcode might provide a solution to accommodate intricate structures within existing memory constraints.

These potential resolutions highlight the evolving nature of technology and its capacity to address current limitations. As computational resources continue to advance, the prospects of implementing intricate lattice designs with finer control become increasingly promising.

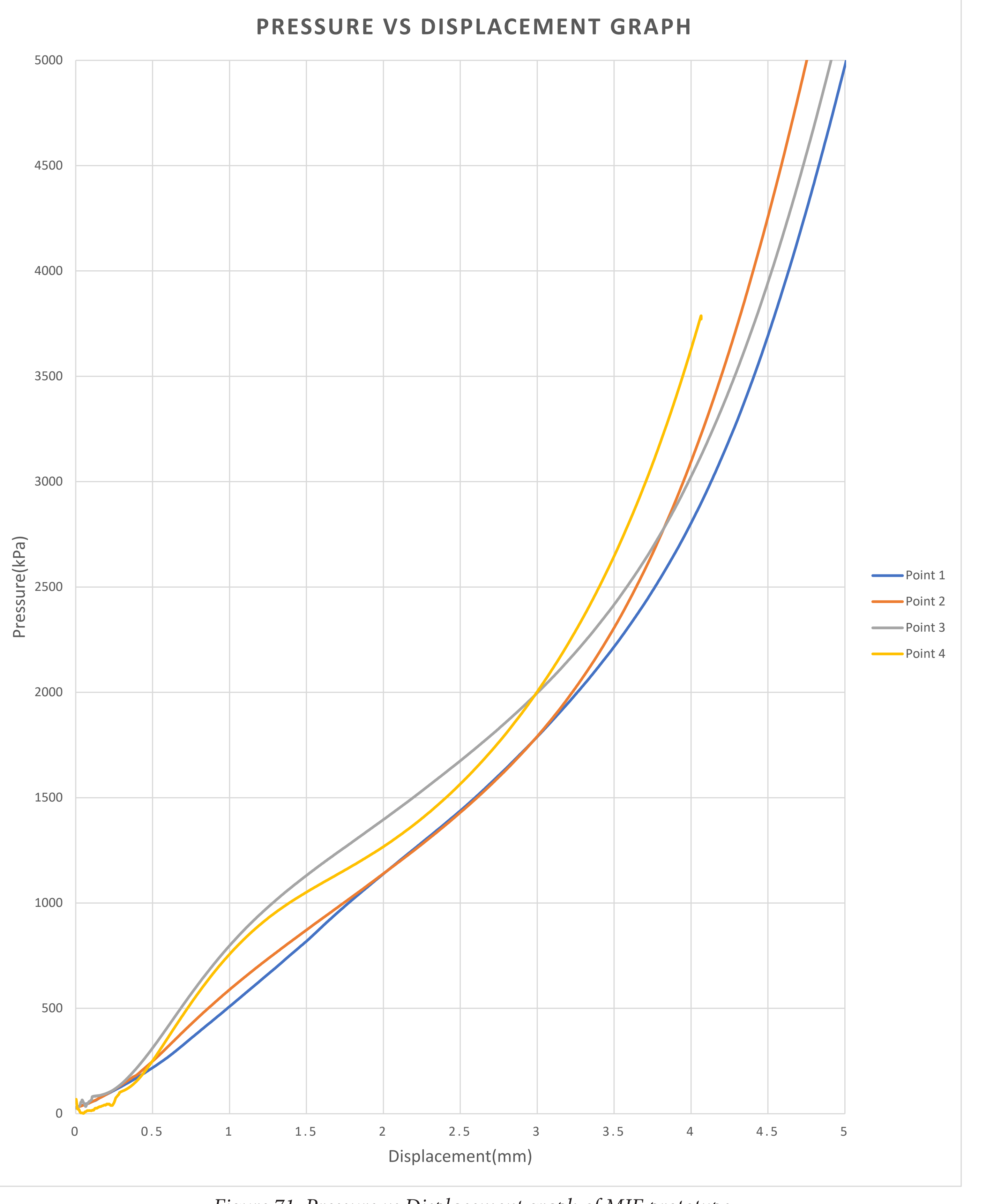

Figure 71. Pressure vs Displacement graph of MJF prototype.

5.3. Cost Estimation

An overview of the costs associated with developing a personalized inlay sole is presented here. These costs are categorized into two parts: the initial investment cost for equipment, and the cost per pair, which encompasses expenses for data collection, material costs, and operational expenses. This estimation is conducted without factoring in economies of scale.

Investment Cost for Equipment:

3D Foot Scanner	€ 2,000.00
Insole Pressure Sensor	€ 1,890.00
FDM 3D Printer	€ 160.00
Total	€ 4,050.00

Variable Cost per pair:

The measurement session for an individual user, considering € 40 per hour labor costs and 30 minutes per participant, could amount to approximately **€ 20**.

The processing could further add another **€ 10.**

For safety shoes, considering the significance of Electrostatic Discharge (ESD), TPU with ESD properties like 3DXSTAT or Essentium TPU-Z ESD can be employed. Each pair of inlay soles utilizes 200g of material, which totals **€22** per pair.

The electricity expenses associated with operating a 3D Printer for 12 hours to produce a pair of inlay soles, consuming 120W, are expected to be minimal.

The subsequent post-processing tasks, such as sanding the inlay sole and affixing a textile layer, are projected to incur costs of around **€ 15** per pair.

Cumulative cost per pair: **€ 67**

This is a reasonable price for a personalized inlay sole and is commercially viable.

6. Conclusion and Recommendations

The culmination of the report comprises valuable Recommendations. Drawing from the project's insights and outcomes, these recommendations provide actionable direction on advancing the project toward a commercially viable solution.

6.1. Discussion

This chapter discusses the result and findings of the project on the Personalization of Safety shoe inlay soles using dynamic foot data.

The project successfully establishes a framework for creating fully personalized inlay soles for safety shoes, tailored to meet the unique needs of individual users. While the focus was on safety shoes, the adaptable nature of the framework allows for its application to other types of footwear as well.. The project introduces a workflow that enables semi-automatic design and manufacture of personalized inlay soles by leveraging users' foot scan and pressure data. FDM 3D printing was identified to be a feasible and viable method of manufacturing inlay soles. Mechanical testing of the Gyroid lattice made from TPU demonstrated its similarity to foam structures, making it ideal for inlay soles. The ability to control the local response by modifying the unit cell size based on pressure data proved to be an effective approach for redistributing pressure and improving overall foot health. Nonetheless, certain limitations in computing and processing methods were identified, impacting the size and thickness of the lattice, highlighting areas for further improvement. Based on these findings, designs for inlay soles were created and iterated based on observations, to finally create a fully functional final design which meets all the requirements of an inlay sole while incorporating features that provide better contact with the foot and reduce pressure hotspots. The validation with users confirmed that personalized inlay soles significantly contribute to comfort, fit, and overall shoe experience, underscoring the value of customization in footwear design.. Additionally, the project successfully demonstrated the cost-effectiveness of implementing mass customization through Fused Deposition Modelling of TPU with ESD properties.

Overall, the project exemplifies the benefits of personalized inlay soles and establishes a workflow that incorporates personalization into both the shape and properties of the inlay sole by utilizing 3D scans and dynamic pressure data. The importance and benefits of personalization was validated with users. The developed framework serves as a solid foundation for Bata Industrials to pursue the commercial development of personalized inlay soles, enhancing their product offerings and driving greater customer satisfaction through individualized footwear solutions.

6.2. Future Scope

This section suggests next steps that can be done to build on the project to convert this into a commercial product offering by Bata as well as alternate directions that can be explored in the project.

Testing ESD - TPU Properties

While TPU with ESD properties is expected to behave similarly to the tested TPU, actual printing and testing using ESD - TPU should be conducted to validate its mechanical properties and suitability for mass production.

Validating the Durability under Field Conditions

In order to ensure the long-term performance and viability of the personalized inlay sole as a commercial product, thorough testing of its durability under real-world field conditions is essential. Implementing a field trial in collaboration with potential end-users and industries would allow for comprehensive evaluation of the inlay sole's wear resistance and robustness.

Automation and Integration of Workflow

To transition the project into a commercial product offering, the designed workflow should be integrated with scanning and pressure sensing systems, and CAD modeling applications. This integration would create a more automated and efficient process, enabling the creation of personalized soles on a larger scale. Collaborating with experts in CAD software development would streamline the workflow and enhance its adaptability to various shoe designs.

Improved Slicing and Gcode Generation

Efforts should be made to improve the slicing process and gcode generation to allow for printing thinner lattice walls and smaller unit cells. achieving finer localized pressure control is critical for optimizing the performance of the personalized inlay sole. Exploring advanced 3D printing techniques and software modifications could facilitate the creation of more intricate lattice structures, as triangular meshing and slicing as per the current workflow is very memory intensive.

Although the project demonstrates one feasible and viable method to produce a personalised inlay sole that provides value to the user, alternate directions of study can also be taken up on the project, as all possible options have not been exhaustively tested and verified.

Testing Different Infills, Lattice structures and Materials:

Continuing the project's exploration, testing different infills, lattice structures and materials could uncover additional options for enhancing the performance of personalized inlay soles. Researching and comparing the mechanical properties and comfort levels of various materials, such as different TPU blends, or TPE, would provide valuable insights into selecting the optimal material for specific use cases.

Investigating Alternative Manufacturing Methods:
Exploring alternative manufacturing methods or 3D printing processes beyond FDM could open up new possibilities for inlay sole production. Techniques like selective laser sintering (SLS) or resin 3D printing may offer unique advantages in terms of design flexibility and material compatibility.

Activity-Specific Pressure Distribution:
Considering the dynamic nature of workplace activities, the project could delve into activity-specific pressure distribution. Understanding repeated tasks in specific working conditions impact foot pressure distribution will lead to the development of task-specific inlay soles, catering to diverse industries and professions.

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Appendix

1. Design Brief

DESIGN FOR our future

TUDelft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Souparnika 6322

initials: A given name: Abhijith

student number: 5484057

street & no.:

zipcode & city:

country:

phone:

email:

Your master programme (only select the options that apply to you):

IDE master(s): [x] IPD [ ] Dfl [ ] SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: [ ] Honours Programme Master

specialisation / annotation: [ ] Medisign [ ] Tech. in Sustainable Design [ ] Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Toon Huysmans dept. / section: HCD

** mentor: Jun Wu dept. / section: SDE

2nd mentor: Christiaan Versteegh

organisation: Bata Industrials/ Bata Nederland B.V.

city: Best country: The Netherlands

comments (optional): Toon Huysmans's research focuses on data driven digital human modelling and simulation. Jun Wu's expertise lies in computational design and digital fabrication.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

TUDelft

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair: Toon Huysmans date: 10 - 03 - 2023 signature: Toon Huysmans Digitally signed by Toon Huysmans Date: 2023.03.10 10:02:57 +01'00'

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 39 EC

Of which, taking the conditional requirements into account, can be part of the exam programme: 30 EC

List of electives obtained before the third semester without approval of the BoE:

* Variant for Engineers

[ ] YES all 1st year master courses passed

[x] NO missing 1st year master courses are:

ID4170 Advanced Concept Design (21,0)

name: Robin den Braber date: 13 - 03 - 2023 signature: Robin den Braber Digitaal ondertekend door Robin den Braber Datum: 2023.03.13 10:20:44 +01'00'

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: [x] APPROVED [ ] NOT APPROVED

Procedure: [x] APPROVED [ ] NOT APPROVED

- the missing course ID4170 has been finished according to the course coordinator

comments

name: Monique von Morgen date: 21 - 03 - 2023 signature:

Initials & Name: A Souparnika 6322 Student number: 5484057

Title of Project: Personalization of safety shoe inlay soles using dynamic foot data

Personal Project Brief - IDE Master Graduation

Personalization of safety shoe inlay soles using dynamic foot data — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 02 - 03 - 2023 — 22 - 08 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The project will be done in collaboration with Bata Industrials B.V. , an international safety shoe manufacturer and nextUPPS. Bata Industrials wants to embrace Industry 4.0 and incorporate new technology to improve their products and production methods. Hence they have partnered with UPPS, which focuses on helping companies (re)design their products implementing personalization through 3D scanning and printing techniques.

People's feet are of very different shapes and sizes and they behave differently dynamically under different conditions; there are a number of parameters that vary from person to person and yet customization of shoes are not done to this extent. A 4 Dimensional foot scanner has been developed in TU Delft (Kwa, 2021; Tajdari et al., 2022) (see figure 1) which is able to capture the dynamic morphology of the foot. This enables us to gather a large amount of data about the feet and how it behaves over time under different conditions such as walking, lifting a load, bending over etc.

The popularization of 3D printing as a viable method of production opens up possibilities of mass customization. It also enables us to alter the internal structure of parts in a way that was impossible with conventional manufacturing methods. Implementing 4D scanning and 3D printing in safety shoe inlay soles, which determine the comfort and pressure distribution to the feet, enables us to create highly personalized shape and stiffness profiles by altering the shape, fit and internal structure of the inlay soles, based on the temporal foot deformation data.

Academic studies that are conducted to determine the right position and shape of metatarsal pads (Chen et al., 2015) and heel Pads (Goske et al., 2006) rely on methods such as simulating the behavior of foot using finite element modeling and analysis of the feet, bones and tissues. This does not accurately represent the actual scenario where feet are of different shapes and sizes and may behave differently under actual conditions. Personalizing inlay soles is conventionally done by podiatrists taking measurements of the foot, wax molds or silicon pads . A few companies like Aetrex are developing personalized inlay soles using pressure mapping and 3D scanning. Previous studies examining 3D printing of the inlay soles used data from plantar pressure measurement (Jandova et al., 2020) (Davia-Aracil et al., 2018). Introducing the 4D dynamic data in this field can substantially improve the quality of results.

Bata's interest to invest on the development of this technology provides an opportunity to use the resources available to them for the project. The importance of the end product of the project is highlighted by several studies that have shown that personalized, conforming inlay soles give users health benefits and prevent several foot and lower limb conditions. However, devising a methodology for testing the prototypes is a difficult task, as the effect of a personalized inlay sole may not be immediately apparent within the short time frame available.

Davia-Aracil, et al. (2018). 3D printing of functional anatomical insoles. Computers in Industry
Felix Kwa (2021) Design of an accurate and low cost 4D foot scanner for podiatrists
Jandova, Sona et al.(2020). Development of 3D Printed Insoles.
Chen, W, et al. (2015). Plantar pressure relief under the metatarsal heads – therapeutic insole design using three-dimensional finite element model of the foot.
Goske, S,et al. (2006). Reduction of plantar heel pressures: Insole design using finite element analysis.
Tajdari, F., Eijck, C., Kwa, F., Versteegh, C., Huysmans, T., & Song, Y. (2022). Optimal position of cameras design in a 4d foot scanner. In 42nd Computers and Information in Engineering Conference (CIE) [V002T02A044] (Proceedings of the ASME Design Engineering Technical Conference; Vol. 2). The American Society of Mechanical Engineers (ASME).

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Personal Project Brief - IDE Master Graduation

introduction (continued): space for images

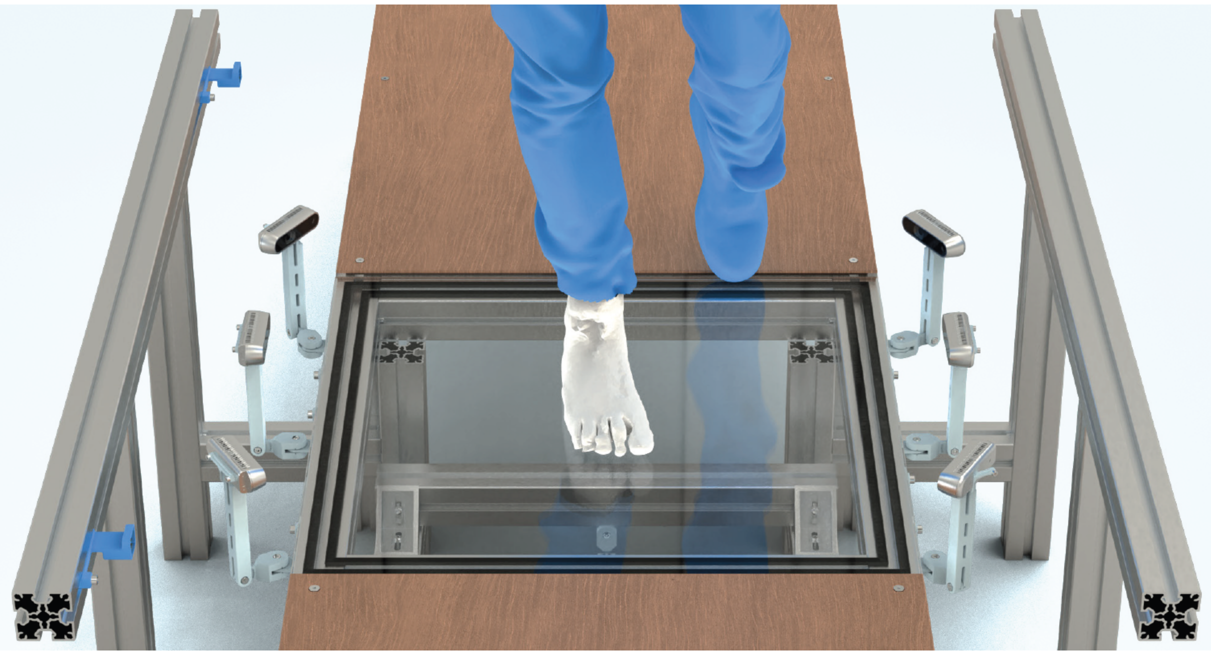

image / figure 1: 4D foot scanner (Kwa, 2021)

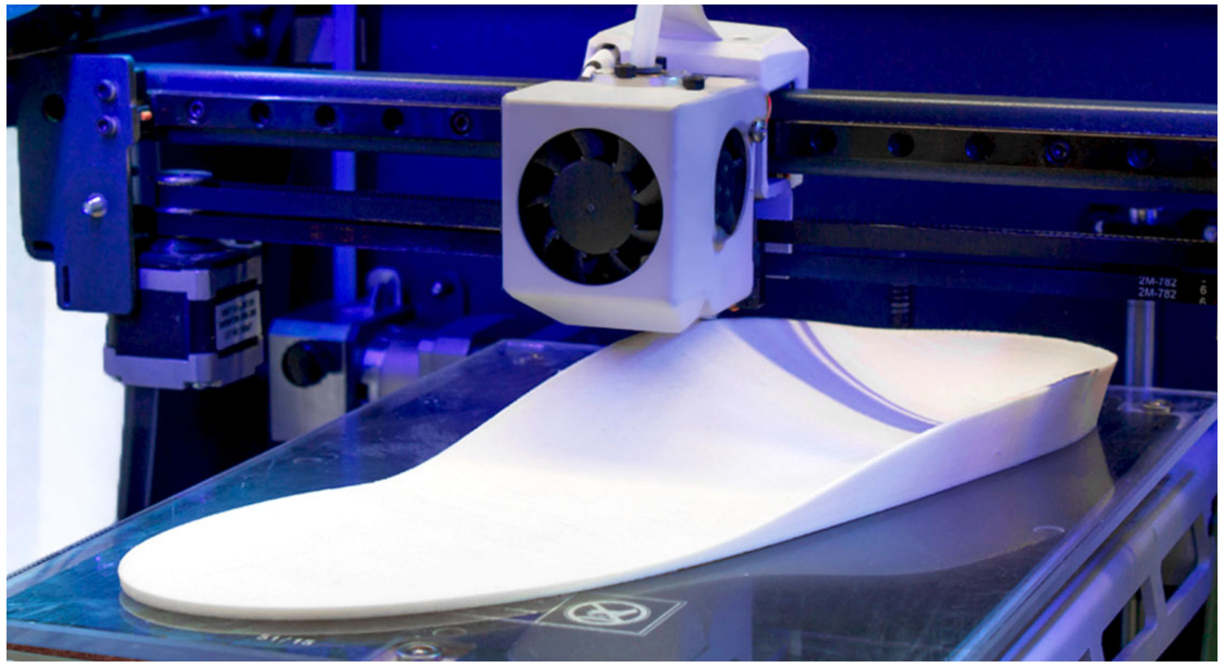

image / figure 2: 3D printing of inlay soles by Zoles

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Even though there is a large amount of variation in the shapes and sizes of people's feet, there is limited personalization being done on the safety shoes produced at Bata Industrials. The aim of the project is to develop a design methodology to use the dynamic morphology change data collected using 4D scanning of feet, and dynamic pressure mapping from a pressure mat, in creating a personalized inlay sole (footbed) that can be inserted into safety shoes (with focus on the area of the ball of the foot). The quality of the raw 4D scan data acquired has to be analysed to see if it can be refined into a format that can be used. Recommendations have to be made on the structure of the data output so that it could be readily used. Information thus obtained has to be processed to derive shape and stiffness information and explore the options to manufacture them through 3D printing. The possibility of utilizing 3D printing to customize an existing semi finished inlay sole has to be explored. The creation of this method to extract parameters for the inlay soles from temporal scan data and using it in manufacturing, will enable Bata to implement mass personalization in the future.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Through the project, I will explore how to analyze and process the dynamic data into ergonomic comfort and shape/stiffness information of the inlay sole, which can be produced using 3D printing. The final deliverable will be a methodology for the design and manufacture of (slightly larger) inlay soles based on foot data, combined with a prototype of the personalized inlay sole which can be put in a modified shoe with a larger space for it.

Research has to be done into the functions of different components of the inlay sole and the functionality they provide. Dynamic data has to collected from different sources like the 4D scanner, pressure mats and also any existing literature. The dynamic morphological data from the 4D scanner has to be investigated to extract useful data regarding local deformations during various activities. Recommendations have to be given on what improvements have to be done on the scanner to provide better quality results for future projects. The information extracted will be used to provide insights on the important parameters of the foot and how it could affect the comfort. Using this data and parameters, methods of manufacturing an inlay sole, possibly building on existing semi finished inlay soles to customize them has to be explored and prototyped. This project will open up the future possibility to automate the process of inlay sole design and manufacturing based on data extracted from 4D scans which can be used in personalization of products by Bata.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 2 - 3 - 2023   22 - 8 - 2023 end date

	Week Start Date	27-Feb	06-Mar	13-Mar	20-Mar	27-Mar	03-Apr	10-Apr	17-Apr	24-Apr	01-May	08-May	15-May
	Week End Date	03-Mar	10-Mar	17-Mar	24-Mar	31-Mar	07-Apr	14-Apr	21-Apr	28-Apr	05-May	12-May	19-May
	Calender week	9	10	11	12	13	14	15	16	17	18	19	20
	Project Week	1	2	3	4	5	6	7	8	9	10	11	12
	Working Days	2	5	5	5	5	4	4	5	4	2	5	3
	Cumulative	2	7	12	17	22	26	30	35	39	41	46	49
Preparation	Kick off	X											
Preparation	Research about ergonomics of foot												
Preparation	Collecting Info from 4D scanner & databases												
Preparation	Visiting Bata Plant												
Development	Extracting foot information												
Development	Converting Information to Shape & Stiffness map												
Development	Midterm											X	
Development	Creating CAD of insole												
Development	Printing Prototypes												
Testing	User testing												
Testing	Methodology derivation												
Testing	Greenlight												
Report	Reporting												
Report	Presentation												
Report	Video												
	Graduation												

	Week Start Date	22-May	29-May	05-Jun	12-Jun	19-Jun	26-Jun	03-Jul	10-Jul	17-Jul	24-Jul	31-Jul	07-Aug	14-Aug	21-Aug
	Week End Date	26-May	02-Jun	09-Jun	16-Jun	23-Jun	30-Jun	07-Jul	14-Jul	21-Jul	28-Jul	04-Aug	11-Aug	18-Aug	25-Aug
	Calender week	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	Project Week	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Working Days	5	4	5	5	5	5	5	5	5	0	0	0	5	2
	Cumulative	54	58	63	68	73	78	83	88	93	93	93	93	98	100
Preparation	Kick off														
Preparation	Research about ergonomics of foot														
Preparation	Collecting Info from 4D scanner & databases														
Preparation	Visiting Bata Plant														
Development	Extracting foot information														
Development	Converting Information to Shape & Stiffness map														
Development	Midterm														
Development	Creating CAD of insole											Summer Break			
Development	Printing Prototypes														
Testing	User testing														
Testing	Methodology derivation														
Testing	Greenlight							X							
Report	Reporting														
Report	Presentation														
Report	Video														
	Graduation														X

Off days	
Good Friday	07-Apr
Easter Monday	10-Apr
King's Day	27-Apr
Off Day 1	03-May
Off Day 2	04-May
Liberation Day	05-May
Ascension Day	18-May
Day after ascension	19-May
Pentecost	29-May

Dates	
Kickoff Meeting	02-Mar
Mid term	09-May
Greenlight	06-Jul
Graduation	22-Aug

The project is broadly divided into 4 phases. The method of approach is to have short Iterative loops employing reflection in action.

Phase 1 – Preparation
Research on Foot ergonomics and Inlay sole functions from literature and visiting Bata Industrials.
4D scan data collection and extraction from the TU Delft scanner (Kwa,2021; Tajdari et al., 2022).

Phase 2 – Development and Prototyping
Extracting foot information and its biomedical interpretation.
Development of inlay sole general geometry and specs / shape & stiffness map
Explore 3D print options, part construction and creating semi-finished goods.
Personalized CAD design and prototyping of the inlay sole

Phase 3– Testing
Testing the inlay sole effectiveness with the user using a shoe from Bata and reference inlay sole.
Iterations based on the inferences.

Phase 4 - Reporting
Preparation of deliverables for the project and presentation.

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TU Delft

MOTIVATION AND PERSONAL AMBITIONS
Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

My main motivation of choosing design and taking up Integrated Product Design course was to discover ways to utilize new and emerging technologies in products to improve user's experience and quality of life. 3D printing and scanning open up possibilities of mass personalization which was impossible with the conventional technologies. By taking up this project with a company, I believe I can be in the forefront of adopting these technologies and utilizing their potential to enhance the safety and comfort of the users. I believe as a designer, I can provide a holistic and user centered approach to the process. I personally want to work on a project that is of significance to the industry and can directly lead to the development of a future commercial product or system. The collaboration with Bata ensures this.

The ergonomics centered project I did in association with the European Alliance for Sports Engineering Education and Magura brakes gave me insight into the nuances and challenges in evaluating user ergonomics. It is a difficult, yet interesting field that I want to explore more about.

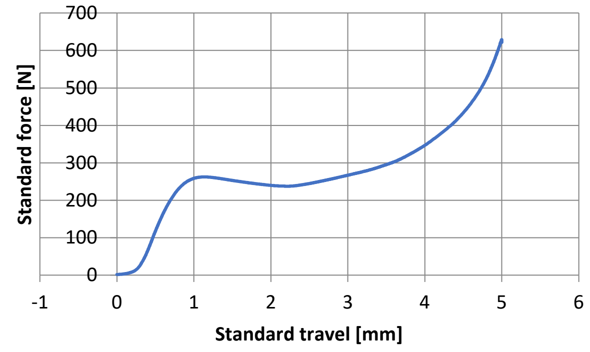
Through this project, I also want to explore parametric design, learn to utilize tools like grasshopper and learn methods to design using topology optimization/ lattice structures. I want to learn more about 3D and 4D scanning and gain experience in converting the data into usable information. I am intrigued by 3D printing technologies and love to experiment with FDM printing during my free time. I believe this project will enable me to look into different types of 3D printing and also explore the flexibilities and opportunities it provides.

FINAL COMMENTS
In case your project brief needs final comments, please add any information you think is relevant.

2. Compression Test Results

The individual Force- Displacement graph of the samples tested in section 3.2 is given here. The contact cylinder had a diameter of 60mm.

25x25x25



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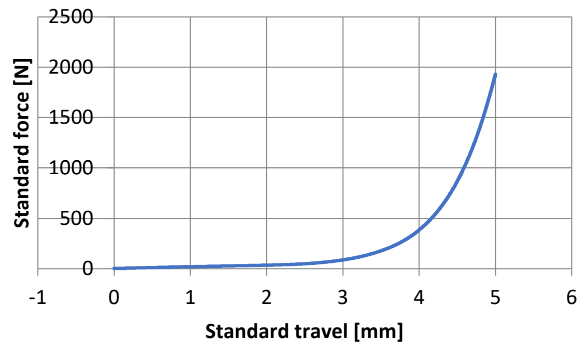
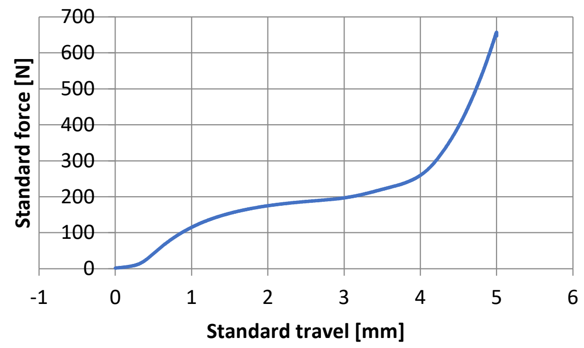
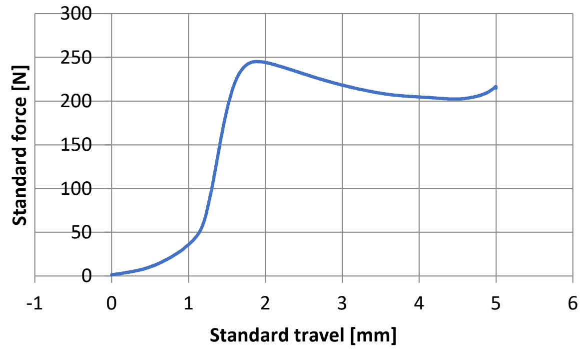


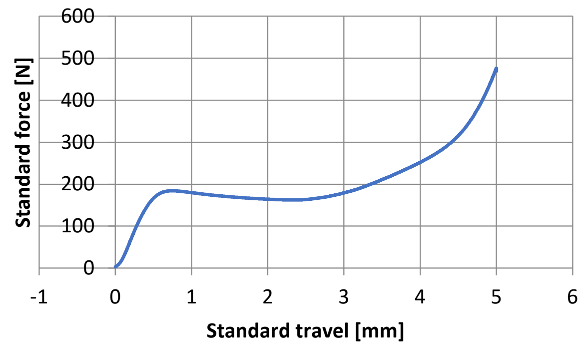
B-25x25x10



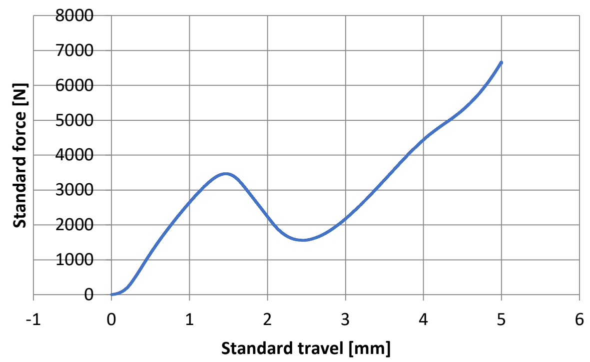
b- 25x25x50



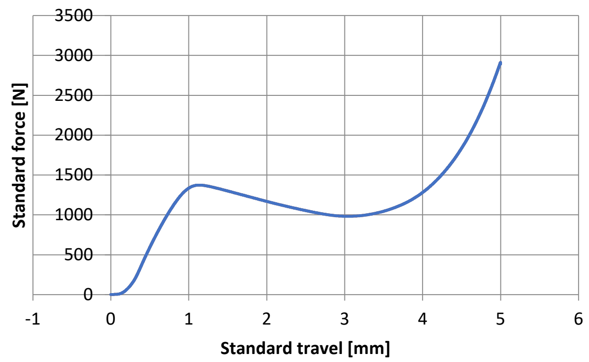
25x25x30



5x5x25



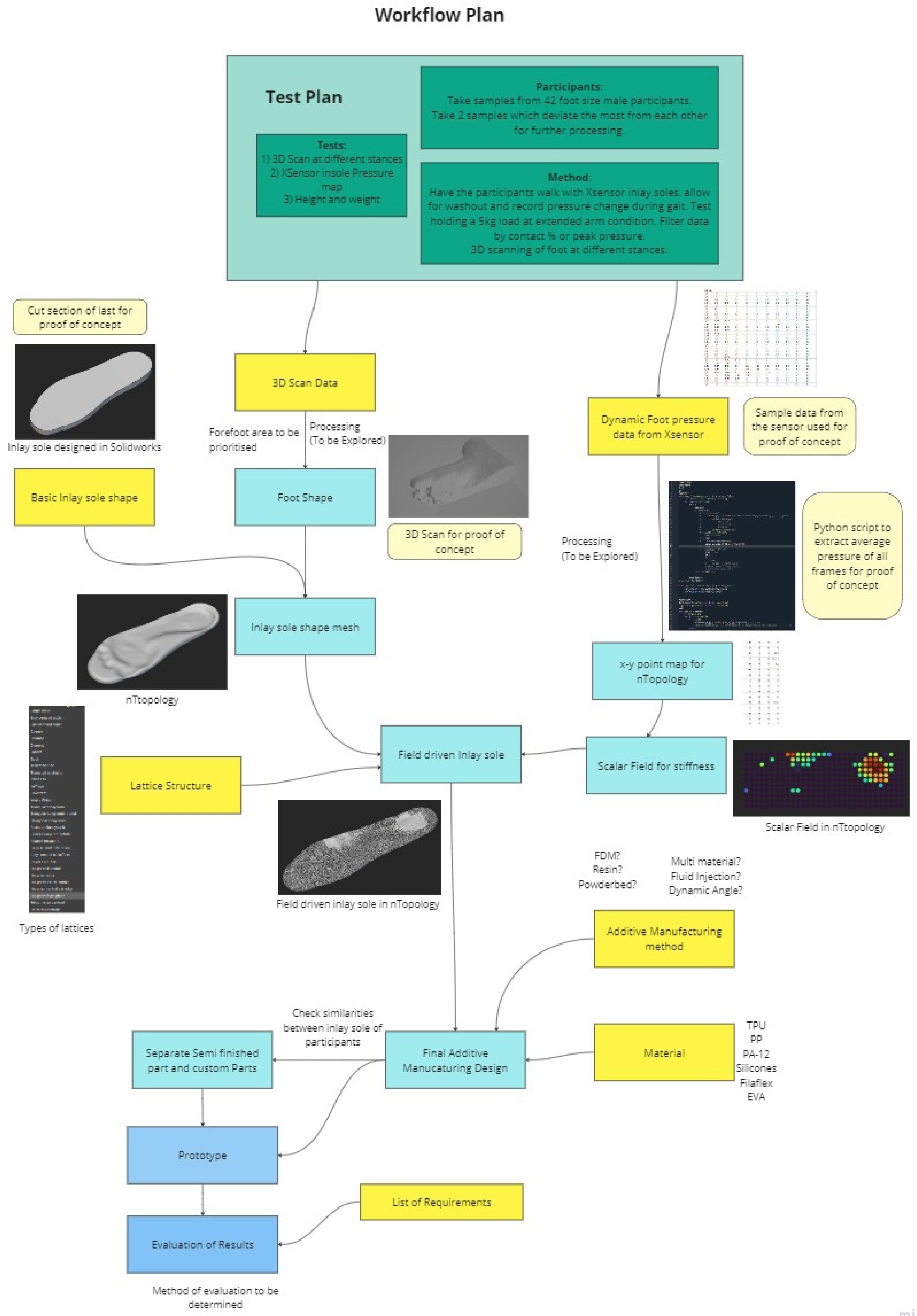
10x10x25



3. Python script to convert Xsensor pressure data to Ntop pointmap

```python
from pathlib import Path
import PySimpleGUI as sg
import csv
read=False
county=0
clndata=[]
findata=[]
#POPUPS
input=sg.popup_get_file("Choose source file", multiple_files=False,)
if not input:
    sg.popup("Cancel", "No file selected")
    raise SystemExit("Cancelling: no file selected")

OUTPUT_DIR = sg.popup_get_folder("Select an output folder")
if not OUTPUT_DIR:
    sg.popup("Cancel", "No folder selected")
    raise SystemExit("Cancelling: no folder selected")
else:
    OUTPUT_DIR = Path(OUTPUT_DIR)
opfilname = sg.popup_get_text('Enter file name', title="Textbox")


with open(input) as csv_file:
    csv_reader = csv.reader(csv_file)
    for row in csv_reader:
            if len(row):
                if row[0] == "FRAME":
                    read = False
                if read:
                    clndata.append(row)
                if row[0]=="SENSELS":
                    read= True

for y in clndata:
    countx=8.512
    for x in y:
        findata.append([countx,county,0,x])
        countx-=0.266
    county+=0.266
    if county>24.8:
        county=0

with open (str(OUTPUT_DIR)+'/'+opfilname+'.csv','w') as new_file:
    csv_writer = csv.writer(new_file)
    csv_writer.writerows(findata)
```

4. Workflow Plan



5. Template of Informed Consent Form

Participant ID: ....

Measurement of foot characteristics

This research is conducted as part of the MSc study Industrial Design Engineering at TU Delft.

Contact person: Abhijith Souparnika, 0613229976

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research consists of the following activities:

1. Performing the following tasks while wearing a safety shoe with a pressure sensing inlay sole
   a. Walking for a distance of 34m
   b. Lifting a weight of 5kg
   c. Standing
2. Taking 3D Scans of foot under following conditions
   a. Full body weight
   b. No loading
   c. Toe-off position
3. Testing the custom designed inlay sole and providing feedback through
   a. Interview
   b. Questionnaire

I am aware that data will be collected during the research, such as notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. Data will be processed and analysed anonymously (without your name or other identifiable information). The data will only be accessible to the research team and their TU Delft supervisors.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project.

I give permission for using photos and/or video recordings of my participation:
(select what applies for you)

- ☐ in which I am recognisable in publications and presentations about the project.
- ☐ in which I am not recognisable in publications and presentations about the project.
- ☐ for data analysis only and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes.

I acknowledge that no financial compensation will be provided for my participation in this research.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

The researchers take the applicable COVID-19 measures into account. I confirm to respect the COVID-19 measures taken and will follow instruction about these provided by the researchers.

I will receive a copy of this consent form.

________________ ________________

Last name First name

02/05/2023 ________________

Date (dd/mm/yyyy) Signature