Exploring Dynamic Shoes

Vimukthi Gunatilleke
Eindhoven University of Technology
Eindhoven, The Netherlands
s.k.m.v.gunatilleke@student.tue.nl

Naomi Swagten
Eindhoven University of Technology
Eindhoven, The Netherlands
n.swagten@student.tue.nl

Jori van der Kolk
Eindhoven University of Technology
Eindhoven, The Netherlands
jori@vdkolk.cc

Veerle Teigeler
Eindhoven University of Technology
Eindhoven, The Netherlands
v.teigeler@student.tue.nl

Abstract
This paper describes the explorations done to envision dynamic forms of the upper part of shoes. We utilized the emerging technology of Rapid Liquid Printing (RLP), in an attempt to realize the dynamic shoes. The research is thereby built up of two parts; exploring methods to incorporate dynamism in the upper part of a shoe as a means of aesthetics and expressing the way people walk, as well as the building of a Rapid Liquid 3D printer. Various material explorations were done with silicone material in order to understand its versatility and form possibilities. Our research also looks into the possible future of shoe design using RLP and creating dynamism through the production of pneumatic cavities within the silicone that allow fluids and gases to flow in and out of them.

Author Keywords
Digital manufacturing; 3D printing; Dynamic; Shoe design; Deformation; Rapid Liquid Printing; Dynamic shoes,

Introduction
We explored shoe design in a context of embodied wearables, where the shoes would be an extension of the person wearing them. This resulted in us exploring ways to bring more dynamism and expressivity to shoes. Through understanding the possibilities of dynamics, we can gain a better insight to which new

materials, shapes and forms allow for an interesting and exciting expression of movement, within a shoe.

We also looked into a recently developed printing technique, called Rapid Liquid Printing (RLP) [7] where we try to produce such a shoe to explore these dynamics. In order to create this dynamism, we aimed to create pneumatic cavities within the upper part of the shoe which would be printed using RLP. this enables us to fine-tune and precisely define where and what these pockets should look like.

Traditional shoe production does not allow for customization as it relies on mass production of the elements that make up a shoe. 3D printing technology, however, allows for ultra personalization in almost every element of the shoe. Solemaker, for example, 3D prints personalized and customizable shoe soles [6].

By using RLP , we try to push the boundaries of 3D printing technology. RLP allows the object to be printed without any support material. This is done by directly printing into a hydrogel, which keeps the printed artefact suspended in place, until the printed material cures [7]. This allows for more form freedom by eliminating the need of layer by layer printing.

Related work

Rapid Liquid Printing

RLP is a technique that has been developed by M.I.T.'s Self-Assembly Lab to make furniture for a company called Steelcase [7]. The main concept involves printing an immediately curable liquid, in a vat of gel. "The gel is similar to a hair gel or hand-sanitiser and has two key functions. The first is that it can suspend objects so that we aren't fighting gravity and we don't require layer-by-layer printing or support materials" - Skylar Tibbits for WIRED magazine [12].

Being the machine

Devendorf and Ryokai research into the "values of art practice to suggest new configurations of humans and machines in hybrid making and present *Being the Machine*, a system that guides users in building 3D models from everyday materials by following instructions typically given to 3D printers" [4]. We adopted this technique to do initial explorations with printing silicone both on fabrics and in the gel.

Reconfiguration in objects

Reconfigurable objects are defined as objects that can be deformed either by the user or an automatic system. In a research by Kim et al [8], reconfigurable objects were collected and compared. Three kinds of materials were found; elastic, stiff and hybrid. Stiff objects occured to have the least amount of deformation possibilities, while elastic objects had the most deformation possibilities. A hybrid material, combination of both stiff and elastic, might be used to deform the elastic parts while still be able to regulate the shape. Elastic materials can be deformed in perception of softness/hardness by rolling it, inflating it, or changing its state [8].

Deformable shoe sole

Reconfiguration has also been applied in commercial shoes. Reebok released the "Reebok Pump" which was the first shoe which could inflate deformable air pockets in the heel of basketball shoes [6]. To make these innovative shoes, the pumping mechanism of a ski boot was adapted in a sneaker [2]. The aesthetic appearance of the Reebok Pump was new at the time and therefore perceived as innovative. The inflatable shoe was also functional; due to the pump mechanism a user could customize the shape to a more personal fit.

Nike has been releasing shoes with air cushioning units since 1982 [1]. Tinker Hatfield revolutionized shoe design by making the air units visible in the Nike Air

Max, inspired by the visible pipes of Centre Pompidou [9]. The air cushioning units were integrated, because it results in more comfort while moving [1].

Neonatal Simulations
Reconfigurable objects are also applied in health care. For his PhD thesis, Mark Thielen is developing "high anatomical and physiological fidelity resuscitation mannequins" [13] for doctors to practise cardiopulmonary resuscitation on newborn babies. He used an MRI scan of a baby to 3D print functional organs and internal structures out of silicone[13]. The blood flow within the silicone organs is mimicked by using valves similar to human blood vessels.

Soft robotics
Soft robotics is a research topic which looks into the development and realization of robotics with soft bodies, which are made of "easily deformable matter such as fluids, gels, and elastomers" [3]. Soft robotics often use pneumatic networks as an actuating mechanism. These networks consist of small tubes filled with fluid or gas that are incorporated in the robots limbs [3]. By pressurizing or de-pressurizing the tubes the robot can move part(s) of its body.

Sarotis Experimental Prosthesis
Researchers Ava Aghakouchak and Maria Paneta from Bartlett School of Architecture had an interest in exploring the body-space relation through deformable technology. They did research on a wearable that inflates when it senses an obstacle is near in a physical or digital space where the person's "awareness of space could be amplified using live 3D scanning technologies that control the inflation and deflation" of the soft robotic wearable. The researchers found that haptic feedback can be used to navigate participants to in a virtual space [10].

Deformation in shoes
In order to design futuristic shoes, we had a look into common shoe trends by observing the different types of shoes which were worn in the centre of Eindhoven in April 2018. During this observation, we saw many low-top model sneakers. The Nike Air Max, Nike Air Force 1 and Adidas Superstar were very common among the people on the street. Figure 1 shows a shoe with such air cushioning unit in the sole.

Figure 1: During the field trip, we saw many shoes with air pockets in the sole (like this shoe) which deform while walking, creating a cushioning effect.

The air pockets in the sole allow for comfort, and seem to influence the walking experience. These visible air pockets inspired us to explore whether air pockets could be used to create an aesthetic upper part of a shoe.

The goal was to create a shoe which deforms while walking, to create new aesthetics and give the wearer a new overall walking experience.The paper prototypes in

Figure 2 show the possible form of a shoe which we imagined would deform whilst walking.

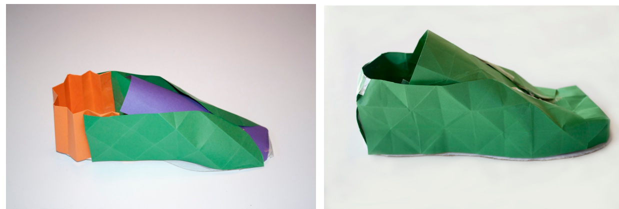

Figure 2: Two shoe prototypes made from paper were made to explore the form of a deformable shoe.

Figure 3: A sketch of a deformable shoe which adapts its shape while walking; when someone stands, there is pressure on the sole and thus the air pockets are inflated.

We envisioned the sole as a kind of pump, we wanted to inflate and deflate the air pockets on the top of the shoe. The sole and air pockets would be connected to allow fluid flow to and from the sole and air pockets, as is visualized in Figure 3.

Material Selection

Since we aimed to design a shoe which can deform while walking, we started selecting materials which had shape changing qualities.

Plastics can deform through inflating [8]. We explored the inflatability of plastics by means of stitching, as can be seen in Figure 4. While inflating the stitched plastics, it showed a breathing behaviour. These explorations helped us to understand the result of the stitching patterns and how they influenced the way the prototypes inflated.

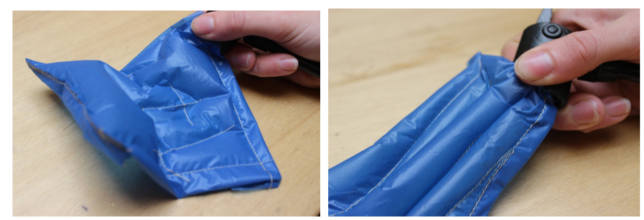

Figure 4: Pumping stitched plastics showed a breathing behaviour, due to the stretchability of plastics.

There are several reasons why we chose to work with silicone over plastic. Firstly, silicone could be used both in the printer and for the dynamic explorations done by hand. Secondly, silicone comes in many different types with different properties.The printer needed a silicone with a low viscosity and preferably a 1:1 mixing ratio of the two components, so it could be easily extruded. It also needed a to be quite flexible and elastic to manufacture shoe uppers and air pockets respectively. Thirdly, silicone is relatively easy to work with.

Therefore, we settled on "EcoFlex 00-20" by "Smooth-On" because it fulfilled all of the aforementioned criteria (Datasheet in Appendix A)

Upon placing the silicone samples on body, we learned that silicone felt slimy and thus wanted to explore whether it could be used in combination with textiles to give a more natural shoe feel. We did some tests with the combination of silicone and spacer textile generally used in sneakers (Figure 5). The open structure of the spacer allowed the silicone to soak into the fabric, effectively creating a new hybrid-material. Adding silicone on the top of spacer textile resulted in a more natural tactile experience.

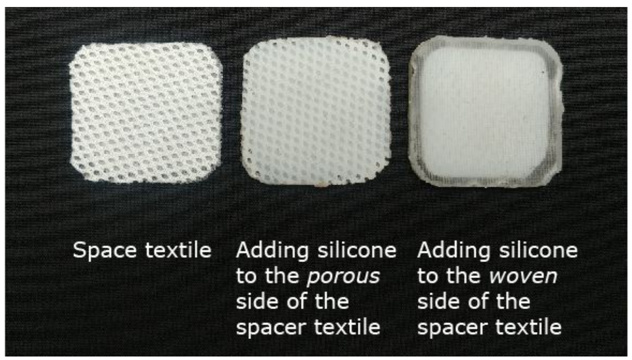

Figure 5: Silicone and spacer fabric tests

Prototyping Dynamic Shoes

In order to examine whether silicone could work to design a deformable shoe we tried to create pockets of air within the silicone, which could deform by means of inflation. As can be seen in Figure 6, we created some air pockets by means of tightening parts of a silicone tube with Tie-wraps. When pressing on one of the air pockets the air escaped from that air pocket to the surrounding air pockets.

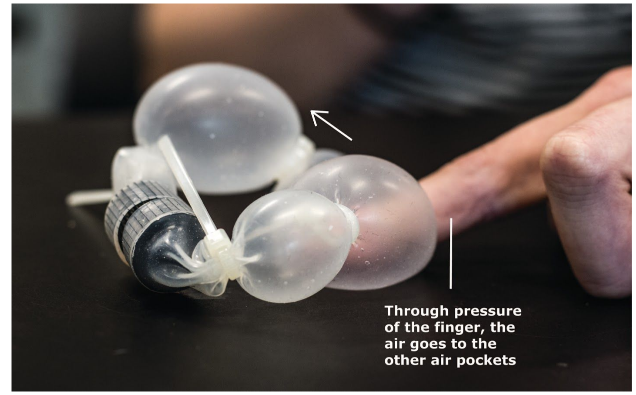

Figure 6: Using pressure as a tool to make dynamic aesthetics with a silicone tube and Tie-wraps.

We tried embodied ideation by placing the prototype on the foot. As can be seen in Figure 7, the air pockets on the top of the shoe got more inflated when standing on an air pocket.

Figure 7: By pressing (left) and releasing (right) the foot to the ground, the direction of air changes in this silicone tube changes.

Since we wanted to design the shape of the air pockets within the upper part of the shoe, we started experimenting on how to create the air pockets in the upper part of a shoe. By using baking paper in between two layers of silicone (Figure 8), we could prevent the two layers from bonding together, effectively forming an air pocket. We could then determine the shape of the air pocket by cutting the baking paper to a desired pattern, as seen in Figure 9.

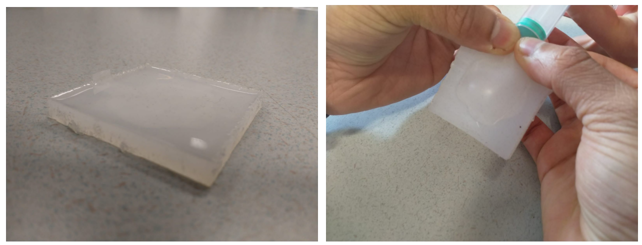

Figure 8: Using baking paper in between two layers of silicone results in an air pocket when inflating it with air.

In order to get the shape of the shoe, we made a wooden mold by using the patterns created by Solemaker which we laser cut. As can be seen in Figure 9, this mold was used to pour in some silicone in the form of a shoe upper, and create the air pockets.

Figure 9: This shoe pattern mold was used to create

a silicone deformable shoe with baking paper that was cut into a pattern and inserted before the top layer of silicone was poured.

Final Demonstrator

Figure 10: The selection of shoe samples that explore various dynamic aesthetics.

The final demonstrators can be seen in Figure 10. Since it was difficult to see the pneumatic cavities inflating (Figure 13), we contacted Majken Kirkegård Rasmussen, an assistant professor and expert focussing on shape changing interfaces. She suggested to highlight the dynamic transformation, by using textiles and fluids, as shown in Figure 11b and Figure 11c.

We also explored colouring the silicone and using intricate patterns like a flower as in Figure 11a. We found that due to the viscous nature of silicone it was very difficult to make detailed patterns, resulting in a overall shape forming without the details.

We explored the possibility of making brand designs with dynamic fluids as seen in Figure 12. This made for an exciting concept design that could be easily realized by companies like Nike.

Figure 11a: Exploration into intricate patterns and colors

Figure 11b: Spacer overlay to highlight the dynamic expression

Figure 11c: Using liquid to highlight the flow of fluid through the cavities.

Figure 12: Showing the inflated Nike Logo through pushing black liquid in the pneumatic cavity.

Figure: 13: Inflated air pockets in one of the shoe designs.

Experiencing dynamic shoes

The prototypes we made attempted to evoke a new walking experience. We asked 10 participants to fit the shoe seen in Figure 13. Once they wore it, the shoe was inflated, and the participants were asked several questions to describe their experience.

Most participants described the shoe to show a living behaviour. For example, one participant stated; *"The shoe has a life on its own, because it is breathing"* Another participant said she would like to influence the behaviour of the shoe to "A more natural expression of my body".

Also, the shoe was found to be comfortable, and fitted nicely to the foot. A participant said; *"It feels really comfortable and gives a massaging effect" and that "It feels as an embodiment of my own skin."*

Next to this, we conducted some questionnaires during Demo Day which provided us with their opinion of the shoes. From the feedback of the questionnaires we received, we learned that the participants do think that a shape changing shoe was innovative and has potential, and that they preferred the shoe to have a coloured liquid instead of air.

Overall, taking into account the aesthetics and the experience of the prototypes we made, we are able to conclude that we did in fact create artifacts that were an aesthetic embodiment of the person's foot.

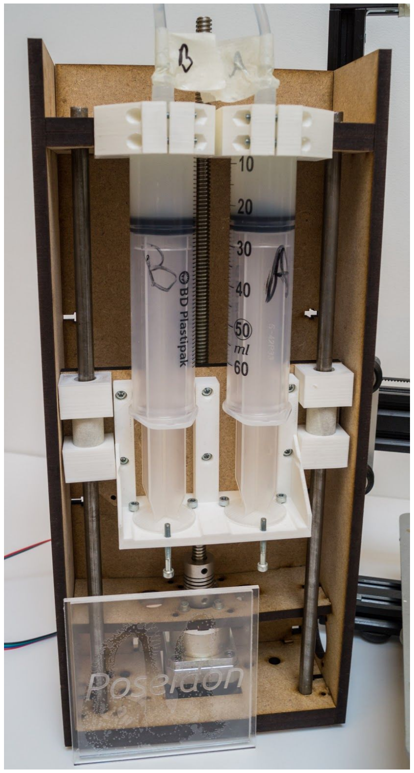

Figure 14: Final version of the modified open-source paste extruders. Both components of a 1:1 viscous material can be extruded

Building the machine

When working on new wearable technology it can happen that the necessary machines are not available. Building your own tools can be seen as an opportunity to push innovation and develop new production techniques.

We envision RLP [7] to be an appropriate technology for creating integrated air pockets in wearable products, shoes in this case. We therefore decided to build our own version of a RLP printer, as can be seen in Figure 15, to test this hypothesis and it would enable us to print silicone shoe uppers containing air pockets.

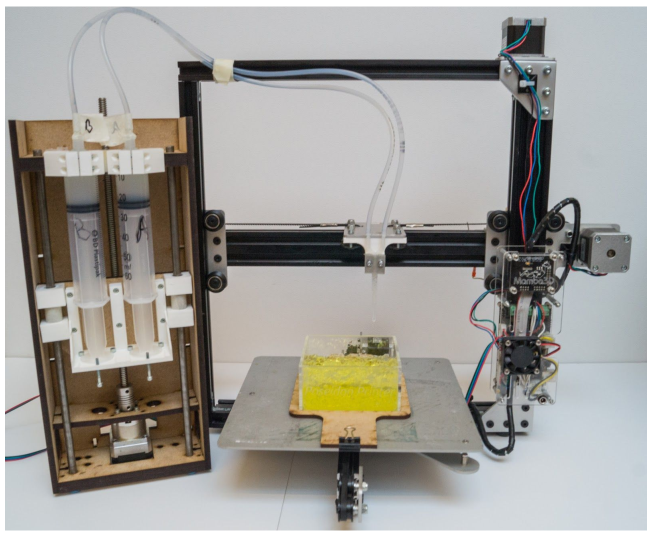

Figure 15: The final version of the printer with a 5 cm tall gel vat and the final version of the extruder.

We took a basic 3D printer and used it as the motion platform for our RLP printer. We modified an open-source extruder, licence in Appendix B, [11] to fit our need and made a custom nozzle that could mix the two components of the silicone just prior to extrusion.

To extrude the two components of the silicone we customized an open-source extruder [11], shown in Figure 14, to house two syringes, this way we would extrude the same amount of both components. We had to change to a geared stepper motor because regular Nema 17's did not have enough torque to extrude reliably.

Figure 16: First working version off the custom nozzle.

The decision was made to mix the silicone in the nozzle, see Figure 16, rather than printing with pre-mixed silicone. Mixing the material in the nozzle had a number of advantages over premixing.
Firstly, less (expensive) silicone material is wasted. With pre mixed silicone we would have to throw away the syringe, tube and nozzle after every print. By mixing the material in the nozzle, the nozzle would be the only part that would have to be replaced regularly.

Secondly, mixing in the nozzle would allow us to print for a longer period of time. Silicone has a set time in which it cures after mixing. This would limit the length of the prints to the pot life, how long the material lasts before becoming unusable, of the chosen material. By mixing the two components in the nozzle, you are not limited by the curing of the materials and therefore the print time is greatly extended.

Thirdly, mixing in the nozzle gave us the option to refill the syringes when they were empty and be able to continue printing right away.

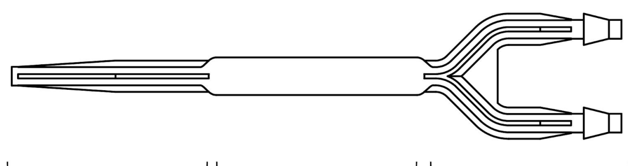

Figure 17: Top: Long Static Mixing Nozzle, all sections of the nozzle are explained (technical drawings in Appendix C).

Our nozzle consist of three parts, the material inlets, the static mixing section [5], and the extrusion tip, as shown in Figure 17.
The material inlet is where the tubes to the syringes are connected. Both inlets come together just before the mixing part of the nozzle.
In the static mixing section, mixing fins thoroughly mix the two components of the silicone. This is the most important part of the nozzle as it determines the success of the curing process.
The extrusion tip is meant to give the nozzle its desired length. The length of this depends on the height of the gal vat, the taller the gel vat, the longer the extrusion tip.

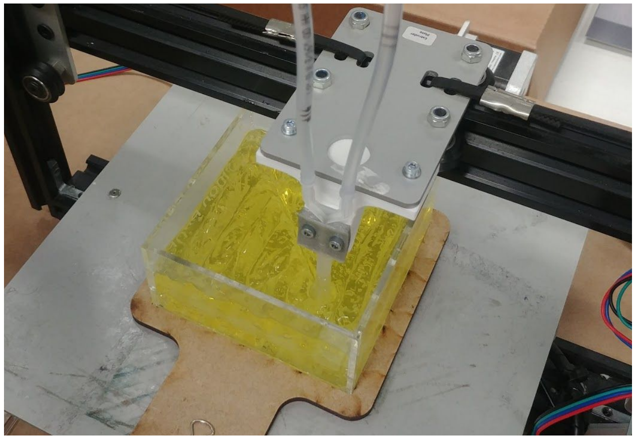

Figure 18: The printer in action during the demo day exhibition.

We did a number of test prints, first on paper to dial in the amount of material being extruded, and later in the gel itself, see Figure 17.

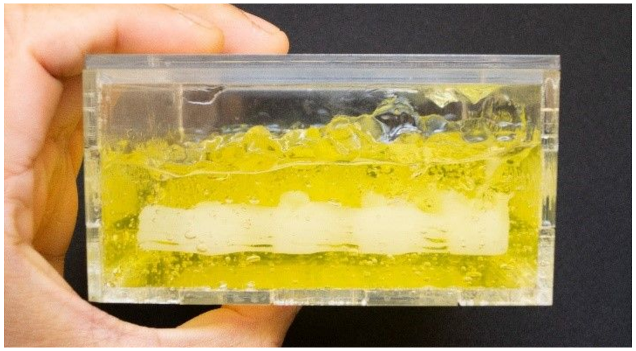

Figure 19: Printed sample in the gel.

The success of these prints, shown in Figure 19, showed that we had successfully built a 3D printer for RLP. Extrusion in the gel was successful and the silicone

cured properly.
With the proper settings the layers fuse together very well. This gives us confidence that we can successfully print air pockets that will function just as well or better then the casted ones.

Controlling the printer

The G-code of the printer was generated using processing (see Appendix D). The code was adapted from the Solemaker code by Troy Nachtigall, Loe Feijs, and Bart Pruijmboom [6]. Programming the printer manually gave us full control over the movement and material extrusion. It was a very quick and easy method to create test and sample prints, see Figure 20.

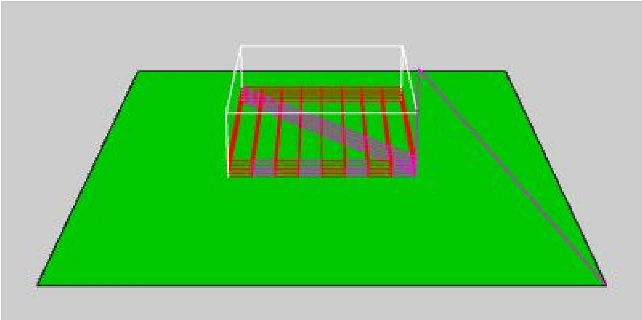

Figure 20: Visualization of the test print made on Demo Day. Purple lines are travel moves, Red lines are print moves. The white lines represent the container of gel and the green represents the bed of the printer. The G-code is shown in Appendix D.

Discussion

Silicone was chosen due to its flexible properties, and the ability to use this in the RLP. After having tried several types of silicone we found Smooth-On EcoFlex to be the easiest to work with. We spent a lot of time on other types of silicone while not getting sufficient results. If we had switched to the appropriate material sooner, we could have made more shape changing explorations.

Silicone is not a breathable material, something that is essential for shoe materials. Would we have had more time, it would have been valuable to find a solution that allowed for breathability in combination with silicone and regular shoe materials.

All the shoe prototypes that we made were not strong enough to walk on, and we only had one shoe instead of pairs. Using shoes that people could wear and experience, we could have conducted better, more conclusive user tests to get an understanding of how people experience wearing the shoes.

Future Work

Developing the initially envisioned shoes would require more research into the aesthetics and functionality of a pneumatic system. In this research we explored coloured liquids and coloured patterns to visualize the pneumatic system.

More research can be done for example in the aesthetic effect of different types of liquids and textures within the air pockets.

In our research we combined silicone with spacer fabric manually. Further research is required to figure out how to combine textiles with RLP. It would be interesting to see if a man-made “fabric” could be printed using RLP.

Research is needed to figure out how to print dynamic shoes with RLP. The aim is to print both the upper and the sole as one part with the air pockets integrated in the print. We have started the development of a method to print integrated pneumatic systems using RLP. There is currently being looked at the option of filing a patent on this method. We therefore need more research to validate that our method can meet the requirements. We fully intent to keep working on this and hope to develop the technology to an extent that it can be deployed in the industry.

Since the RLP technique allows for form freedom, it opens the door to create a shoe that is customized to the customers feet. To gather this foot data, proper foot scans need to be developed, that can be translated into code that the printer can use. An essential step is to develop prototypes along with podiatrists and other experts like physiotherapists. This ensures that the dynamic shoes provide the proper support to the foot.

Conclusion

This research provides some initial insights into the design and making of dynamic shoes. The research looks at the possibilities when it comes to making and designing transformable shoes. One deformable shoe exploration showed a feasible implementation of dynamics by utilizing some logos.

While exploring the possibilities of dynamic shoes we developed and built a 3D printer that will be able to print the shoes and soles with integrated air pockets. RLP is proving to be a promising technology to create air pockets, and are currently developing a new method to print integrated air pockets into the shoes.

The RLP can become relevant in the area of advanced rehabilitation, because it could potentially print customized prosthetics. In general it can make production processes easier, because RLP does not require a mold in the production process.

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