Exploring Mechanical Meta-Material Structures through Personalised Shoe Sole Design

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ABSTRACT

Mechanical meta-material structures (MMS) are designed structures with mechanical properties not found in ordinary materials. MMS can now be created far more easily using digital manufacturing. We explore how different MMS can be combined, through the design of a shoe sole. Thereby showing the potential of using MMS to create personalized and sustainable footwear. We analysed the phenomenon of foot deformation and mapped different structures with different behaviours to meet the needs of different feet. Consequently, a shoe sole was generated by an algorithm and 3D printed in one single material with multiple properties (e.g. stiff and soft) and responsive behaviour, making it easy to recycle. We report the design phases which required using six types of software. Our findings reflect the complexity of this process given the limited availability of software tools that support it. We conclude with a list of requirements regarding tools to further explore MMS.

CCS CONCEPTS

• **Human computer interaction (HCI)**;

KEYWORDS

Mechanical Meta-Material Structures, Generative Design, Digital Manufacturing, Shape Change, Footwear

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Figure 1: Renderings of Personalized Shoe Soles using MMS

1 INTRODUCTION

Mechanical meta-materials (MM) are designed structures with mechanical properties that are not found in ordinary materials. Although MM have been invented at the start of the 20th century, the current availability of digital manufacturing techniques such as 3D printing facilitate the creation of these material structures [Zadpoor 2016]. Thereby they are opening up new possibilities for design, for example in the context of footwear which is still strongly influenced by traditional practices and consequently unable to scale bespoke production to attend to user's actual physical needs. This project addresses two topics. Firstly, exploring the combinations of 3D MMS behaviour in a shoe sole aiming to show the potential of these materials as a possible answer to the need of creating more adaptable footwear (see e.g. figure 1). Secondly, understanding and exposing the complex infrastructures needed to explore the inherent qualities of MMS (see figure2 and figure 3). Through our original study of MMS in an applied footwear context we recognize the enormous potential of MM for future product design, while exposing the current needs in development of tools for designers to better explore these materials. The final insights of this project aim to build bridges between design, computing, mechanical engineering, physics and material science.

2 RELATED WORK

3D printing of flexible structures has opened opportunities in both 2D and 3D mechanical meta-materials. For example, Ion et al. [Ion et al. 2016] developed several 2.5D structures with mechanical properties and showcased a single material door locker mechanism made of a combination of 2D cell structures. The advantage of such system is that no assembly parts are needed as the new mechanism

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is 3D printed in one single material. This also shows the sustainable impact such technology can have in product design.

A second project illustrates how MMS can change the texture of a surface [Ion et al. 2018]. By varying the thickness of a hinge (see figure 3), the researchers were able to control the shape of the surface. Another application of 3D mechanical meta-materials are 3D cells that support the creation of structures with programmable properties [Coulais et al. 2016]. By simply orientating the position of the 3D cell in the structure the I/O can be designed according to the designer's preference. Although this technology is still at a very early stage of development, advantages in a myriad of application domains such as wearables, rehabilitation or mechanical designs have been demonstrated. These qualities are particularly noteworthy as they can replace traditional mechanical/electrical actuators and allow for new interaction. Finally, KinetiX [Ou et al. 2018] establish a basic 2D structure in which the direction of the hinges controls the behaviour of the surface. This mechanism enables highly complex shape-changes using very simple geometries. In terms of applications, these materials are still quite far from being adopted. The closest to application may be Ion et al. [Ion et al. 2018] who demonstrate the value of such mechanical systems through the design of shoes with two different types of outsole grips which may be valuable when users wear the same shoe during different environmental conditions. In particular, because shoe manufacturers have been scrutinizing the possibility of generating designs using digital fabrication while embedding user data in the process [Adidas 2017]. Personalization in shoes with several attempts to mass personalize footwear services by footwear industry include projects by New Balance, Under Armour ArchiTech Futurist or Future Craft by Adidas [Adidas 2017; Piller et al. 2012]. We see footwear increasingly interested in foot scanning [Hegde et al. 2016], finite modelling [Cheung and Zhang 2006], algorithms [Feijs et al. 2016], circularity [Nachtigall et al. 2019] and mass customization [Baena Gracia and Winkelhues 2016]. Nachtigall et al. presented a case study in which they demonstrate how foot data can be used to design footwear addressing the aesthetics, comfort, robustness, balance and temperature [Nachtigall et al. 2018]. This study elaborates on their work by adding the potential of combining 3D MMS in shoe soles which may also have sustainable benefits.

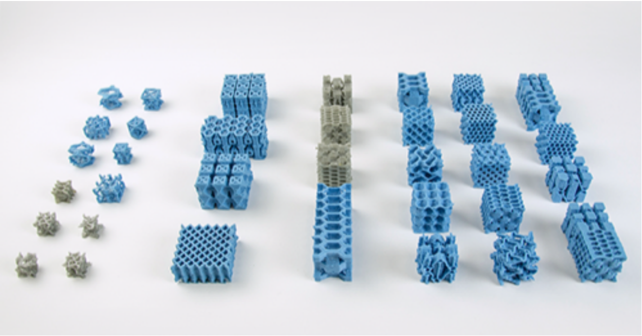

Figure 2: Examples of MMS 3D Printed (FDM) using FilaFlex.

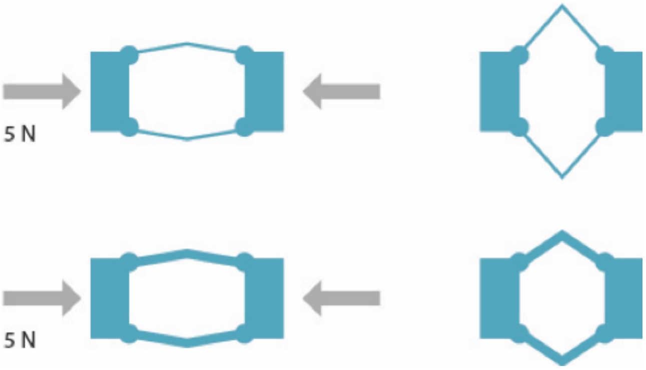

Figure 3: Hinge with variable thickness behaving differently to the same applied force.

3 DESIGN CHALLENGE

Traditionally, shoe soles are divided into three main parts, the insole, the midsole, and the outsole. The material properties of all these parts vary significantly. Depending on the needs of the user, insoles can be found from materials that present rigid to soft properties. With the soft, comfortable insole dominating the majority of the needs of the footwear market. The midsole presents mid-levels of stiffness. This part acts in between the insole and outsole. Most of the support and impact absorption on a shoe sole occurs in the midsole. Whereas the materials found in the outsole (or tread) present the largest levels of stiffness as the bottom part of the shoe relates to stability and protection. Usually, all parts are made of different materials that are combined using traditional adhesion techniques such as gluing, stitching or vulcanization. Some of these methods are unsustainable because they do not allow to easily recycle the shoe sole. If the whole shoe would be made from one material, the recycling process would be considerably simplified no longer requiring material separation labour. Inspired by both industrial and academic advances in MM we developed a MMS shoe sole. By describing our design process, we discuss the challenges in this domain and point to relevant research directions, in particular regarding infrastructure requirements to explore MM.

3.1 Design Process

In the following section we discuss how we explored the mechanical meta-materials' concept of material behaviour programming and discuss how user data influenced the creation of the final footwear piece design. Our research through design approach consisted of five main phases:

1. Understanding of meta-materials behaviour and possible combinations by gathering a set of designed structures and classifying them by behaviour;
2. Collecting data from a user's foot shape change, from both unloaded and loaded position as well as its pressure maps, i.e. the distribution of the feet in a static position;
3. Analysing the data by understanding the foot deformation and designing the shoe sole behaviour, i.e. mapping MMS to the different pressure areas of the foot to create the intended behaviour;

Figure 4: Schematics of the design process using input of the pressure maps, foot deformation and meta-materials behaviour (left) for the Grasshopper definition to generate the shoe sole design (middle) and preparation of the 3D printing process (right).

(4) Creating the system to generate the shoe sole design;
(5) Preparing the digital geometry for prototyping through the 3D printing process.

Note that the phases sometimes happened simultaneously but we describe them separately for clarity and to highlight the importance of each phase as shown in figure 4.

3.2 Understanding Mechanical Meta-Materials

Mechanical Meta-materials require designers to think differently than with traditional materials. Instead of being concerned with the property of a material and adapting the product to these properties, with MM the material performance is designed according to the needs of the application. Therefore, more than understanding the material compound of which the MM is made, designers need to also understand the material structure behaviour. Several types of behaviours can be found in 2D and 3D structures when these are mechanically stressed. Examples are expansion, contraction, twisting or snapping. Although our understanding of how to influence a structure to behave in a certain way can be seen as quite simple, the complexity emerges when different structures are combined. Figure 5 illustrates examples of MM design and their intended behaviour under mechanical stress. By combining two structures with these behaviours it is possible to design a shoe sole that can responsively adapt to the foot's behaviour (see figure 6). Therefore, the shoe sole can have a shape closer to the foot when its unloaded and adapt responsively to the shape of the foot when it is loaded.

3.3 Collecting the User's Data

Two elements of data from the user's foot were required for this project. First, there was the need to have access to 3D digital models of the user's foot of both unloaded and loaded position (figure 7) which was achieved by 3D scanning the foot in both states. For this part of the process the Artec Eva manual 3D scanner was used. The unloaded state was scanned with the foot resting on a chair), while the loaded state required the user to stand on a (transparent) acrylic platform. This data was crucial to understand how the foot changes shape between the unloaded and loaded states. The information was used to further design the behaviour of the shoe sole. Second, it was essential to acquire data of the different parts of the foot's pressure areas. Therefore, the user had to walk on a treadmill capable of measuring the foot's pressure zones in both static and moving scenarios. With this data, it was possible to assign a MM behaviour to the foot's dynamic needs by mapping a structure behaviour to certain areas of the foot by image pressure maps.

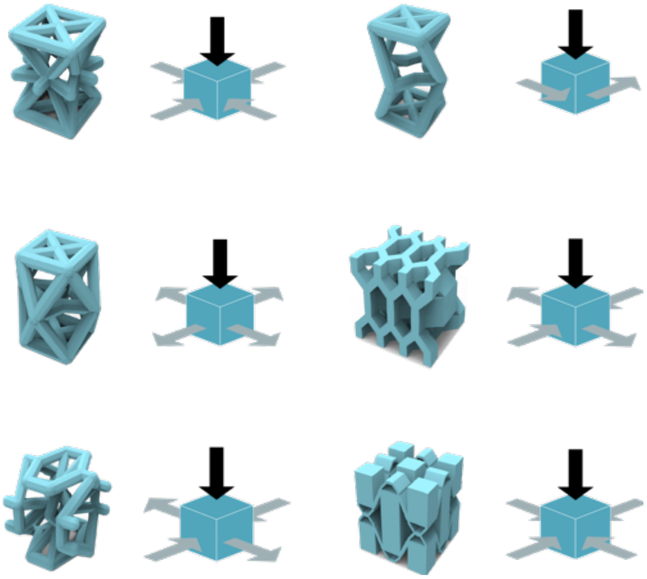

Figure 5: Taxonomy of 3D stress behaviours of MMS. Structures with the cylindrical beams are better suited for 3D printing types such as SLA or Multi-Jet while structures with straight walls (two bottom right) would also be appropriate for 3D printing using FDM processes.

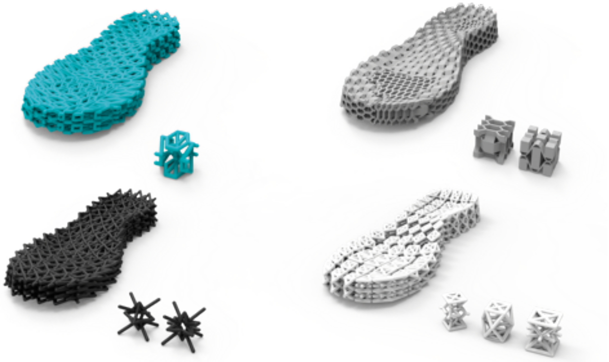

Figure 6: Soles generated from different model goals of 3D stress behaviours of MMS.

3.4 Analysing and Designing the Sole Behaviour

After removing the unnecessary parts of the 3D scans using the Artec Studio software, the files were imported as meshes into the NURBS curve modeler software tool, Rhino 3D. To understand the foot deformation, the scans of both foot states were overlapped in Rhino (figure 8 left), providing the designers with visual feedback of the foot differences in both states. In addition, Rhino allowed for precise measurements in the changes of foot dimensions. According to this method of analysis, the foot expanded to all sides with the bigger change occurring in the length direction of the foot, i.e. from the toes to the heel. At this point, all information required to create the shoe sole was gathered: a library of MMS and their behaviour; shapes of the foot and pressure zones of the foot pad; and the behaviour of the shoe sole in its different areas (figure 8 right).

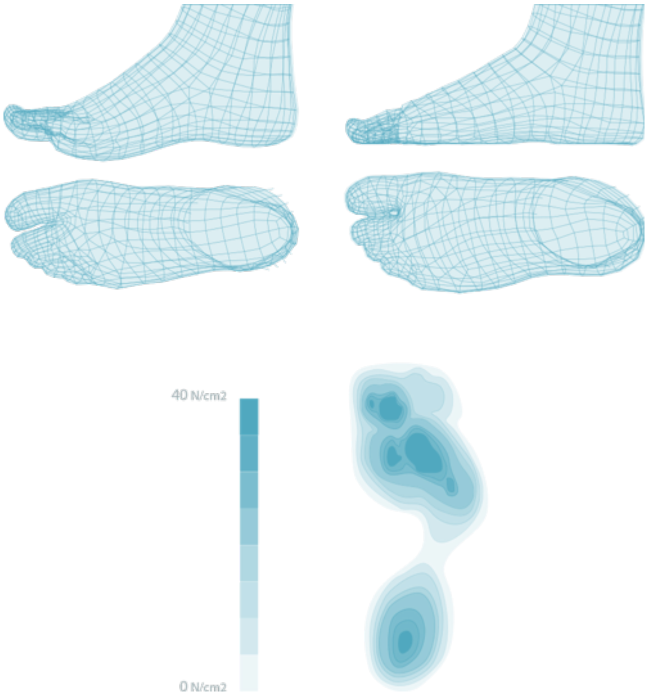

Figure 7: The unloaded versus the loaded foot including the pressure scan.

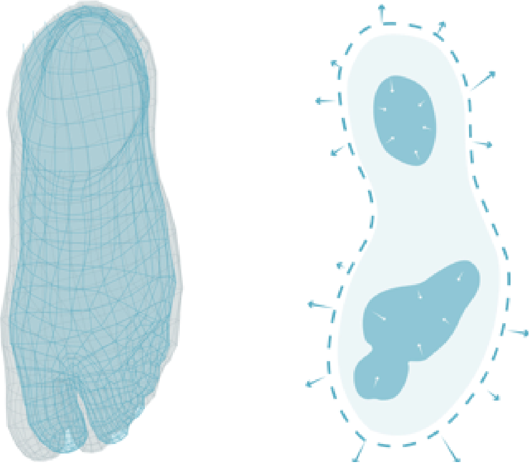

Figure 8: Overlap of the unloaded and loaded foot (left) to analyse foot's deformation (right).

3.5 Generating the design

To build the generative design program to assist in the creation of the personalized behaviour of shoe soles we used Grasshopper (GH), a graphical algorithm editor integrated in Rhino. Our program allows generating designs with MM for any shoe sole geometry by only using three requirements as input (figure 4): the top and bottom surface of a sole geometry; the image of the pressure areas of the foot; and a library of various MM. To illustrate the essence of the algorithm function, we briefly explain the key points of the program created for this study.

(1) First several surfaces were created in Rhino representing the top and bottom of the volume geometry related to the insole, midsole and outsole. These surfaces serve as reference for the generative design program to populate the in between space with MMS, thereby, creating the volume density of the soles, see figure 9 purple colour groups. In addition, all previously created MM designs are uploaded to the same file see figure 9 black groups. However, the algorithm created for this project, only accepts geometries which are converted to meshes. Other geometries, such as surfaces or lines would also work, but required slight changes in our algorithm. In GH a reference component was created for the surfaces while for the MM designs each structure has to be linked to a mesh component. The information about the structures and the surfaces are now stored in GH.

(2) The second step addresses the creation of a function that analyses the image of the pressure maps of the foot. In GH, this part is often referred to as "image sampling". In essence, this function reads the RGB values from an uploaded image and facilitates the use of these results to perform operations

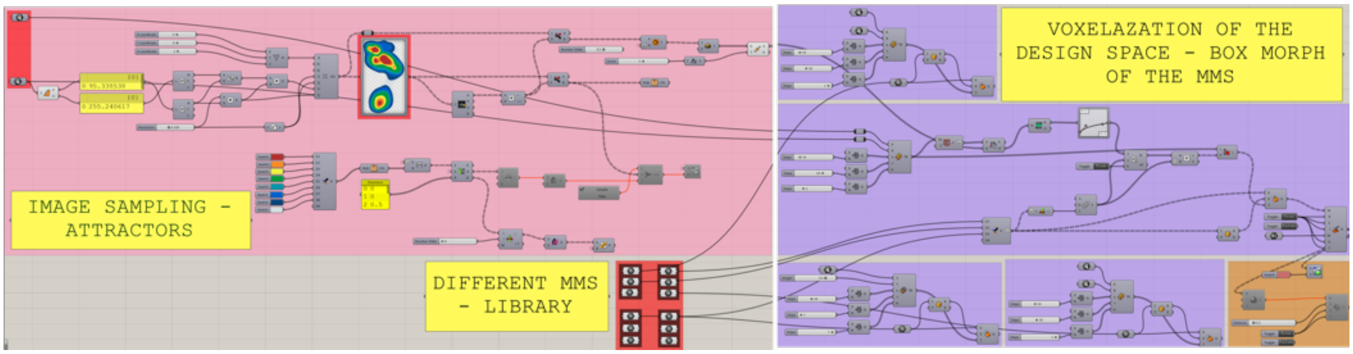

Figure 9: Schematics of the Grasshopper algorithm. The components in the red groups represent the three main inputs, the design space of the sole, pressure maps of the foot and a library of MMS. The components inside the pink area represent part of the algorithm that creates the different attractor point based on the RGB color of the image sampling component. The components in the black groups are the different MMS with distinct behaviors. In the purple groups are the different parts of the shoe sole (i.e. insole, midsole and outsole). This part of the algorithm voxelises the design space while filling the voxels with the MMS that perfectly morph according to the overall space geometry. Lastly, the orange groups smooth the mesh and allow for thickness control of the MMS geometries.

on the geometry in GH, see figure 9 pink colour group. For example, it creates a grid of points on the image leaving only the points that match the previous selected RGB values as geometry.

(3) These points are then used as attractors, which guides the positioning of the MMS on the sole. The third step concerns the creation of a responsive voxelization between the top and bottom surface of the selected in-, mid- or outsole. By using the twisted-box component, it allows controlling the voxel resolution in all 3 axes, see figure 9 middle purple colour group. This part of the algorithm makes it possible to responsively morph the MM to the other inputs, the surfaces and the pressure maps
(4) The last phase addresses creating the thickness of the MMS and exporting the geometry to an .STL format to prepare it for 3D printing, see figure 9 orange colour group. Although the algorithm allows to generate the thickness within the GH definition, errors were noticed when executing that operation as the offset operation was not operating correctly. An alternative was found by simply exporting the geometry before the thickness operation in GH after which the exported geometry was exploded in Rhino and the offset was made as rendered in figure 10.

3.6 Preparing for 3D printing

The current exploration was optimized for printing with a Fused Deposition Modelling (FDM) 3D printer. Yet, the method can be followed for any other 3D printing process. The 3D printer used for our tests was an Ultimaker 2 Modified to 0.8 nozzle thickness. The 3D printer nozzle and feed assembly was hacked to extrude the material Filaflex. Filaflex is a TPE-s which was chosen as it presents a responsive behaviour, due to its 800% resilience, and shows notable qualities such as spring, flex, bend and elastic properties. Through an iterative process we investigated the most appropriate structure design, thickness and reinforcement beams. In addition to the tests

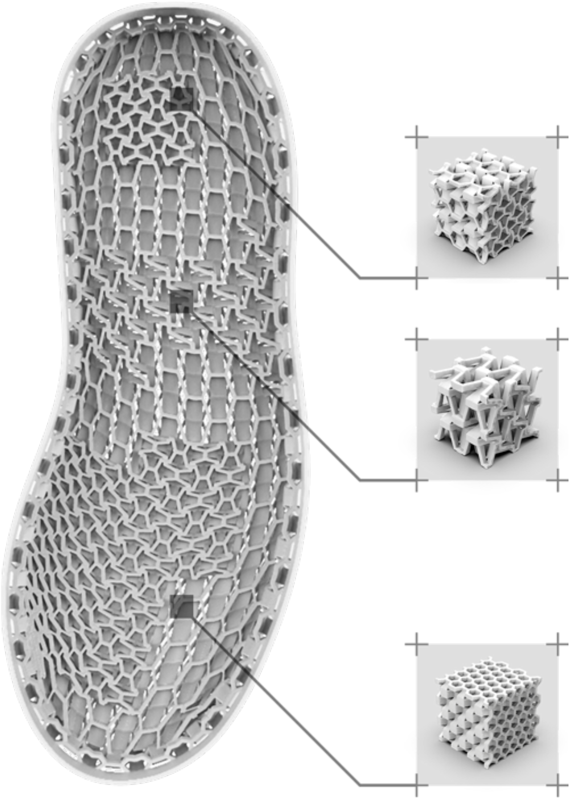

Figure 10: The MMS is applied in areas of the sole heel impact absorption (heel), cushioning transition (middle), responsive deformation (front).

Figure 11: Sole tests, including insole, midsole and outsole tests 3D printed (FDM) in Filaflex.

on the 3D printer, two MMS models were created from paper. These models matched all required behaviours for the purpose of this study and more clearly express the behaviour of the structures (see figure 12 for representation of the behaviour). Consequently, these designs were tested in the 3D printer using the default settings of the machine. Figure 13 shows the outcome of the improved 3D printing results of the new MMS designs. Furthermore, the models partly presented their characteristic behaviour. The structure's geometry was modelled in Rhino, exported as .STL and imported into the software slicer for 3D printing models, Cura. From this program, we created the G-code file which was read by the 3D printing machine. Preparing the file for 3D printing was time intensive and required the use of different types of software (Magics, Meshmixer, Netfabb and Cura) as the geometries exported from GH required several adaptations to make them suitable for 3D printing.

4 DISCUSSION

This project revealed to be very challenging on several aspects. Particularly understanding MM combinations of structures behaviour; optimizing structure design to FDM methods of production; dealing with software issues that concern intuitiveness; and limitations to generate designs using MM. On the other hand, digital fabrication and the multiple properties of MM, show the opportunities that future of footwear can gain from these technologies. The principle of designing a structure that behaves in a certain way seems quite simple (figure 5). However, the complexity changes when structures are combined as it becomes very difficult to imagine what will happen when they are mechanically loaded. At this stage, it may be most appropriate to rely on computational simulations or animations that can illustrate the potential outcome of combining MM. Furthermore, techniques such as Kirigami can support the prototyping process when designing and thinking about MM. This Japanese art form served to understand the structure behaviour more clearly and created possible designs for this type of 3D printing (figure 12). Another approach would be treating the data as a material itself [Nachtigall et al. 2019].

In the process described above, the current off-the-shelf tools and their limitations inhibited the process and required a complex pipeline of software. Comparing the loaded vs unloaded foot was difficult. There is a need for new methods for designers to work with behaviour over time in modelling software. While this has been discussed as a form of sketching and prototyping [Frens et al. 2017], it is vital for personalized fabrication on a production level as well. The exploration process of MM is yet at a very early stage. Through our iterative process we discovered a gap in infrastructure and documentation that supports designers in using MM. Over the course of our project it became evident that a large part of the process consisted of adjusting the infrastructure and software at our disposal. Fused Deposition Modelling processes can be inconsistent in their results. There is an opportunity to add real-time feedback to the printer that understands the expected behaviour [Ballagas et al. 2018] and can make real-time changes to the machine code. Nachtigall et al. [Nachtigall et al. 2018] previously addressed challenges

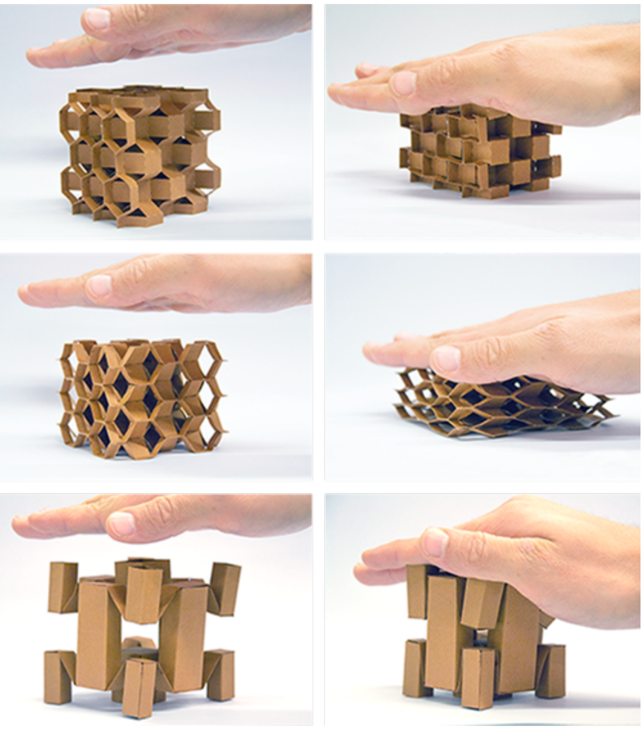

Figure 12: Paper Kirigami models to illustrate the MMS behaviour under stress.

Figure 13: New sole design based upon the gathered insights demonstrating new aesthetic and performance opportunities for near future production.

when negotiating geometry between the several types of off-the-shelf software. The watertight and manifold mesh geometry that is needed for slicer software such as Cura is complicated to generate with the nurb realities of parametric software like GH. Furthermore, GH is not yet optimized to explore MM and is quite complex for beginners. This creates the need of back-end developers to develop front-end software tools to explore MM. We argue that designers should spend more time on understanding and investigating the novel properties of these materials in different application domains to unveil their true potential for real case scenarios, rather than spending time on aligning software programs. The same is true with the hardware and the possibility of reconfigurable machines [Peek et al. 2017] could be advantageous.

4.1 Limitations

The scale of the MM 3D printed samples, in relation to the printing resolution of the Ultimaker 2 used in this study, posed a limitation that did not allow to understand how the thickness variation of the hinges in the 3D printed prototypes affected the MMS behaviour when mechanically stressed. Therefore, it was not possible to test the reliability of the prototypes produced during this study.

4.2 Future Work

Although a great variety of methods to 3D print geometries exist and various studies showcase the value of 3D printing for the exploration of MM, the same cannot be said about software tools that support this process. Therefore, through this paper we wish to reinforce the need for software tools that assist designers in the exploration of MM. Based on our project insights we list our main requirements for such software tools:

(1) A library of MM with animations of their behaviour when certain mechanical stimuli are applied to the structure;
(2) Enable the creation of customized structures before a stimulus is applied. The software should show the possible outcome behaviour, which would be an incentive to explore new structures which ultimately could result in novel properties for the field of MM;
(3) Recommendations for which production method structures (3D Print (FDM, SLS, SLA, DLP, Polyjet), CNC milling, injection moulding) with what materials can be used [Ballagas et al. 2018]. Although the majority of structures are of a complex geometry and only possible to 3D print, for some less complex models, different types of production techniques can be used;
(4) Indication of which MMS can be combined;
(5) Added support for understanding the form and behaviour of the foot as an input (figure 3) is fundamental in combining data to the MMS;
(6) Finite analysis for understanding the dynamic stress and strain in relation to the body locomotion would be ideal.

By developing dedicated software or adding to existing, we foresee more time and opportunities for designers to focus on unveiling the full potential of MM. New aesthetic and performance opportunities become possible as seen in similar process in carpentry [Magrisso et al. 2018] (figure 13). In addition, designers would need less trial and error, saving time and material as the software can predict, recommend and assist users throughout the conception phase of the product design.

5 CONCLUSION

This study demonstrates the complexity designers face when exploring mechanical meta-materials by investigating how MMS could be applied in a specific application domain. We believe that material limitations are currently mainly influenced by budget, therefore we particularly discuss software issues. We argue that there has been insufficient development in this field and propose a set of requirements for software tools supported by arguments from our case study. This paper highlights the need for developing novel or improved software tools that can support the design of applications using MMS, especially for practitioners of shoe design.

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