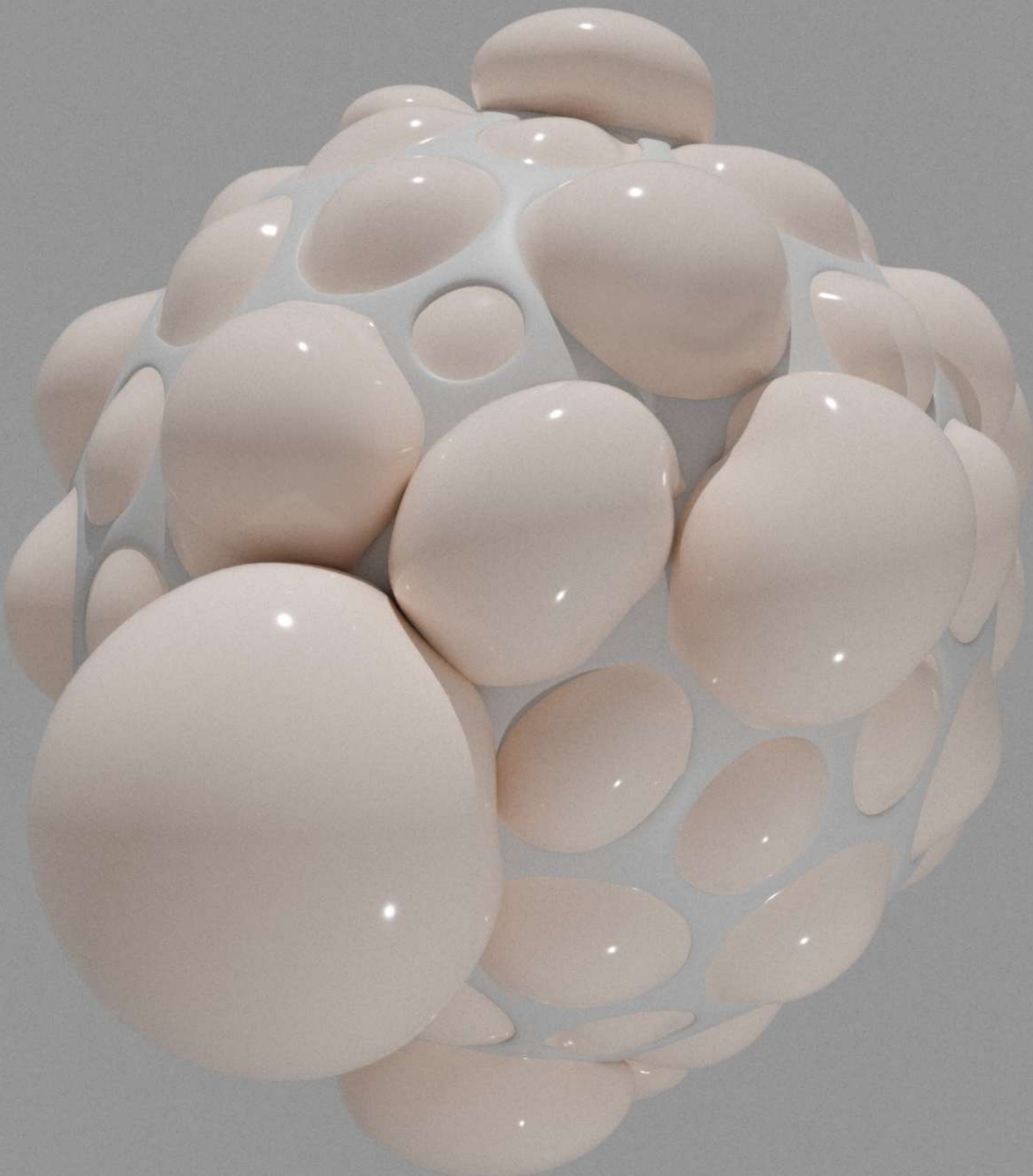
LAURA KEIBLINGER

TU WIEN

COMFORT ZONE



EXPLORING TACTILE PERCEPTION THROUGH AN INFLATABLE WEARABLE

architektur + raumplanung

Diploma Thesis

Comfort Zone: exploring tactile perception through an inflatable wearable

Submitted in satisfaction of the requirements for the degree of
Diplom-Ingenieurin
at the TU Wien, Faculty of Architecture and Planning

by
Laura Keiblinger
01505156

Supervisor: Senior Artist Dr.in techn. Efstathia Eleni Baseta
Institute of Art and Design
Research Unit of Three-Dimensional Design and Model Making
Vienna University of Technology,
Karlsplatz 13, 1040 Vienna, Austria

Vienna, on

Acknowledgements

I would like to express my deepest gratitude to Efilena Baseta for encouraging me to step out of my comfort zone and motivating me to take on this thesis. Her guidance and support have been invaluable. Thank you for the time and care you dedicated to me, always offering feedback and advice. You are genuinely inspiring, and I have learned so much from you. I would also like to thank you for your vital support throughout the robotic printing process and for the opportunity to contribute to your research project *Trans-Bodied Knowledge** through this thesis and the financial support provided through it.

Sincere thanks go to Marco Palma, who generously took the time to introduce me to the robot arm and contributed essential knowledge and support for the robotic printing process.

My heartfelt thanks to my partner Nik for his unwavering emotional support and countless hug trials. Thank you for participating in my hug map experiment and for taking excellent photos of my design.

I am extremely grateful to my parents, who have supported me both emotionally and financially throughout my studies. I owe the completion of this thesis to your generous support.

Special thanks to all my friends for their presence and encouragement in stressful times. I am particularly grateful to Paul, whose inspiring conversations led me to new ideas.

Lastly, I would like to thank Christoph Eigl from the workshop team for milling my mould, which played a crucial role in the fabrication of this design.

*funded by the Austrian Science Fund (FWF) in the framework of the Art-Based Research Programme (PEEK) with Grant No AR 802-G.

Abstract

english.

Body architecture serves as a medium to explore new design methods, materials, and fabrication techniques – shifting the focus from the architectural scale to the human body. As *wearables* are designed to be worn on the body, they provide a unique opportunity to investigate sensory perception. This thesis describes the design and fabrication of a wearable intended to bring awareness to the often-neglected tactile sense. A combination of analogue and digital techniques is employed during the design process. For fabrication, a bio-based material is developed with the aim of achieving properties suitable for robotic 3D printing.

The *tactile wearable* is designed to simulate a hug by applying pressure to the body through an inflatable. Hugging is a universally known tactile experience and a form of deep pressure stimulation known to have a calming effect, even reducing stress. By introducing this immediate contrast from deflated to inflated, the wearable aims to increase the wearer's awareness of tactile sense.

To translate this concept into a design, a hug pressure map, captured through an analogue imprint, is applied onto a digital model, and further processed in computational design software using vertex colour information. The resulting shape features holes that vary in size and density according to the colour map intensity, which in turn determine the location and magnitude of inflation, thus the pressure applied to the body.

A series of tests is conducted to find a material with sufficient viscosity for 3D printing, and enough rigidity to locally withstand the force of inflation once dried. The resulting material is a gelatine-based foam, that is stabilized with xanthan gum and strengthened with the bio-additive wood flour. The wearable is extruded from this material, following a digitally produced path. The inflatable element is made from latex.

deutsch.

Body architecture dient als Medium zur Erprobung neuer Designmethoden, Materialien und Herstellungstechniken. Dabei verschiebt sie den Fokus vom architektonischen Maßstab hin zum menschlichen Körper. Da *Wearables* direkt am Körper getragen werden, bieten sie eine besondere Möglichkeit, Sinneswahrnehmungen zu untersuchen. Diese Arbeit beschreibt Entwurf und Herstellung eines Wearables, das das Bewusstsein für den taktilen Sinn stärken soll. Dabei wird eine Kombination aus analogen und digitalen Entwurfstechniken angewandt. Für die Herstellung wird ein biobasiertes Material entwickelt, das sich für den robotergestützten 3D-Druck eignet.

Das *taktile Wearable* soll eine Umarmung simulieren, indem es über ein aufblasbares Element Druck auf den Körper ausübt. Umarmungen sind eine universelle taktile Erfahrung und Form tiefer Druckstimulation, die beruhigend wirken und Stress reduzieren kann. Durch den unmittelbaren Kontrast zwischen dem nicht aufgeblasenen und dem aufgeblasenen Zustand soll das Wearable das Bewusstsein für den taktilen Sinn schärfen.

Zur Umsetzung des Konzepts wird zunächst der Abdruck einer Umarmung auf ein digitales Modell übertragen und in einer Computational-Design-Software anhand von Vertex-Farbinformationen weiterverarbeitet. Die daraus resultierende Struktur enthält Löcher, die sich gemäß dem Umarmungsabdruck in Größe und Dichte unterscheiden. Sie bestimmen die Stellen und in welchem Umfang das Wearable aufgeblasen wird – und damit, wie viel Druck auf den Körper ausgeübt wird.

In einer Reihe von Tests wird ein Material entwickelt, das über eine ausreichende Viskosität für den 3D-Druck verfügt. Gleichzeitig muss es im trockenen Zustand steif genug sein, um dem Druck des aufblasbaren Elements standzuhalten. Das Ergebnis ist ein gelatinbasiertes Material, das mit Xanthan stabilisiert und mit dem Bio-Additiv Holzmehl zusätzlich gestärkt wird. Das Wearable wird aus diesem Material entlang eines digital erzeugten Pfads extrudiert. Das aufblasbare Element wird aus Latex hergestellt.

Introduction

Research frame

In the summer semester of 2024, I participated in the course *264.256 Artistic Project K - From Space to Wearables* at the Research Unit of Three-Dimensional Design and Model Making (Institute of Art and Design, Vienna University of Technology), during which body experiences were translated into wearable designs. More specifically, the acoustic properties, materiality, character, and use of a space were reinterpreted as haptic experiences – enabled through a wearable. The course provided both theoretical (explicit) and artistic (implicit) input, serving as inspiration for this thesis. This open-ended approach to design allowed for more creative design techniques and experimentation with new materials.

This thesis, *Comfort Zone*, takes place within the framework of the artistic research project *Trans-Bodied Knowledge*[1] which is led by Efilena Baseta and hosted by the Research Unit of Three-Dimensional Design and Model Making (Institute of Art and Design, Vienna University of Technology). The project has received funding from the Austrian Science Fund (FWF) in the Art-Based Research Programme (PEEK, AR 802-G).

Scope

This thesis addresses the prevalent ocularcentric nature of our spatial perception and architectural design, emphasizing the need to acknowledge and elevate non-visual senses. To explore this idea, the thesis proposes the design of a wearable, drawing an analogy between what we wear on our bodies and architectural structures, at best, both entail protection, comfort, and aesthetics. Wearables, being intimately connected to the user, serve as an appropriate medium for studying human senses and indicating spatial perception. Positioned within the peripersonal space, the wearable performs as a body-extension, blurring bodily boundaries.

[1] 'TBK'.

The focus of the design lies on tactile perception. More specifically two parts of this complex human sensory system; proprioception (body awareness) and mechanoreception (touch). While limits or interferences mostly make us aware of haptics[2], this wearable brings awareness by enhancing a playful stimulation – the hug. Making use of the expanding properties of an inflatable, the aim is to apply pressure to the wearer in the same areas a hug would be felt. The goal is not only an aesthetically designed wearable, but also to trigger the tactile sense, subsequently raising awareness of it.

Through a combination of analogue and digital techniques the design is created and fabricated. Starting with the imprint of an analogue human-to-human hug and further processing the resulting colour information digitally to achieve the final design. Given that the design is intended for the human body, the aim is to primarily use natural materials. A substantial part of this thesis focuses on the material studies conducted to develop a biomaterial, aiming to achieve the properties required for the design. This includes a certain viscosity to enable robotic printing, which was subsequently tested.

The thesis is structured as follows: The first chapter introduces inspirational inputs and provides the theoretical background that led to the design idea. This is followed by a review of state-of-the-art projects related to wearable designs and biomaterials. The next chapter presents the design and implementation of the tactile wearable. Furthermore, the material studies are elaborated, leading into an explanation of the fabrication process of the wearable. The final chapter reflects on the outcomes, discusses limitations, and outlines potential future steps.

[2] Jones, *Haptics*.

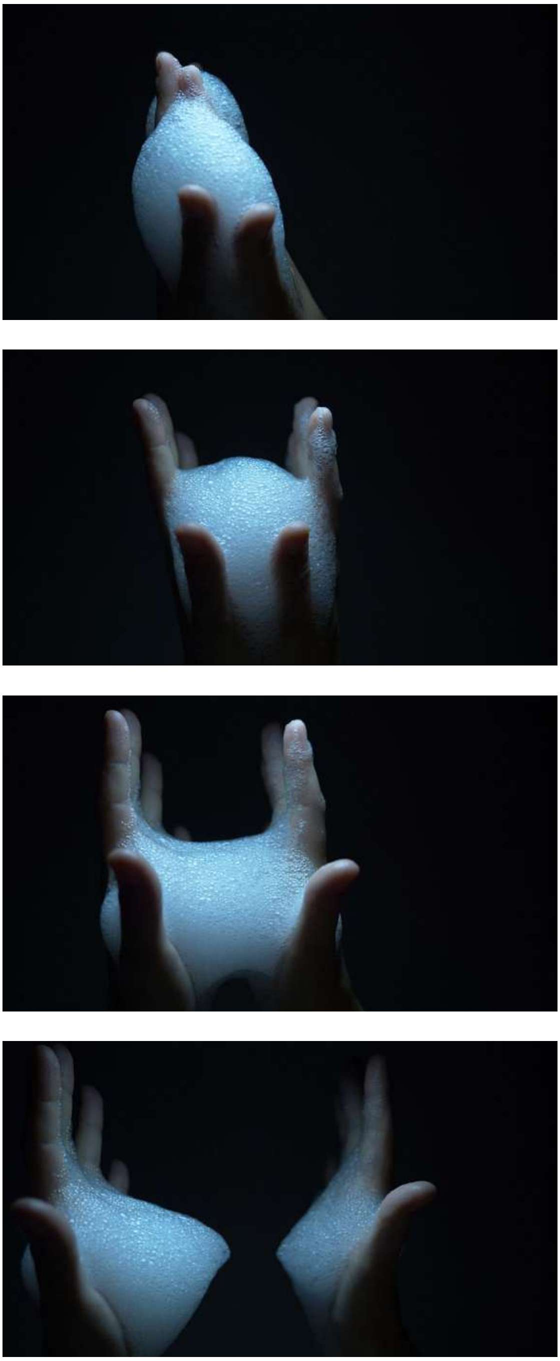
Inspiration

Soap bubbles are a tactile and visual inspiration for the structure of this design. While one soap bubble on its own is fragile, an accumulation of bubbles – soap foam – show strong properties due to their way of arranging as a minimal surface structure. In a two-dimensional space, bubbles will arrange as so that always three bubbles meet and create 120° angles among them. The way bees build their honeycombs follows the same logic. This fascinating natural efficiency of enclosing a space with the least possible amount of surface area,[3] can be used as guiding principal when designing an inflatable object.

When soap foam is pressed together between the hands it creates an even and soft pressure on the skin. When moved apart, foam seems to rebuild its previous shape and then stretches out until surface tension fails. Continuing this hand motion looks and feels like the foam is breathing – or, inflating and deflating. It has a soothing and comforting feeling to it. When a body part is covered in soap foam, one can barely feel it due to its lightness, as it is composed mostly of air. Only the popping of individual bubbles causes a continuous tickling sensation and therefore awareness of it.

The wearable design not only incorporates structural similarities to soap foam, but also explores comforting properties as a central theme. The following pages show images which were taken to capture this inspiration – in movement and stillness.

[3] 'Bubble Sculptures'.



1–4

5

introduction

7

introduction

Awareness of the tactile sense

The dominant role of the visual sense in our technology-driven world leads to a consequent neglect of all other senses. Since architecture is experienced and not just visually observed, being mindful of all our senses is essential. In his book *'The eyes of the skin'* Juhani Pallasmaa argues that working on computers turns the *"design process into a passive visual manipulation, a retinal journey"* and that *"the inhumanity of contemporary architecture and cities can be understood as the consequences of the neglect of the body and the sense, and an imbalance in our sensory system."* Pallasmaa questions the prevalent ocularcentric nature and suggests taking a step back to the root of all senses: the sense of touch.[4]

The sense of touch is composed of tactile sensation (skin) and kinaesthesia (muscles, tendons, and joints). Tactile sensing allows to perceive pressure, texture, temperature, vibration, and pain. It is more of a passive sense which starts to recognise impact already at our hair-ends when being touched. Kinaesthesia, on the other hand, provides information about limb position and movement. Haptic sensing combines these components. It is the active exploration of objects using touch and movement.[5]

Often, the discourse on haptic perception – or the perception of touch – focuses on the hands. When actively exploring form and surface of an object we, in most cases, naturally use our hands due to their mobility and high skin sensitivity. Compared to vision, haptic perception needs much more effort because it takes more time and attention to precisely perceive. When we are not actively exploring something, our skin still receives sensory information. We are usually unaware of this passive perception until we come across limits or interferences. Meaning we need an 'interruption' or active input to become aware of the sense of touch.[6]

[4] Pallasmaa, *The Eyes of the Skin.*
[5] Schönhammer, *Einführung in die Wahrnehmungspsychologie.*
[6] Jones, *Haptics.*

The sense of touch is bound to the *peripersonal space* which is the immediate space surrounding the body in which visual, auditory, and tactile stimulation occurs.[7] However, this space can also form around a tool or wearable, temporarily extending the body. The artist Rebecca Horn utilizes *body instruments* to explore the boundaries of the human body. For the time she wears her design, it is an extension of the body and allows her to touch both walls at the same time.[8]

Artist and computational designer Filippo Nassetti even goes so far as to say that *„[a]ll wearable products, medical devices, tools, and means of transportation, and the city itself can ultimately be interpreted as an extension of our physical bodies.“*[9]

9 Rebecca Horn. Scratching Both Walls at Once. 1974-1975.

[7] Schönhammer, *Einführung in die Wahrnehmungspsychologie*.
[8] 'How Rebecca Horn expanded the boundaries of the human body'.
[9] 'Body Architecture 3.0 – Studio Filippo Nassetti | PAACADEMY'.

Deep pressure stimulation

Our skin can perceive various tactile sensations, one of which is pressure. Pressure is often associated with discomfort. Tight clothing, for example, feels restrictive and unpleasant, and can even result in health-related problems such as a negative effect on body posture.[10]

However, so-called compression vests and weighted vests or blankets are utilized to bring comfort by applying pressure to the body. People who struggle with sensory sensitivity, for example individuals with ASD (autism spectrum disorder), ADHD (attention deficit hyperactivity disorder) or SPD (sensory processing disorder), can benefit from these wearables. For people who are over-sensitive to touch, light touch can lead to sensory overload and even be painful. This 'tactile defensiveness' causes everything to feel more intense and makes many everyday activities difficult.[11]

Deep pressure touch is one method occupational therapists use to help with tactile sensitivity. In contrast to light touch, deep pressure touch is firmer – for example, receiving a tight hug. Through pressure vests and weighted vests or blankets deep pressure is applied to the body which can have a calming and soothing effect, reducing stress and anxiety – overall, bringing comfort. For people who would usually avoid this kind of sensory input, these wearables can be a non-invasive alternative to physical touch.[12]

Marlene Zajicek, an occupational therapist who works with autistic children, adolescents, and adults, shared with me her experiences with weighted vests. She states that even though not all autistic children and adults she works with like them, many,

[10] Sherazi et al., *'Perils of Tight Clothing; A Survey Report'*.
[11] 'What Is Tactile Sensitivity? | Connect n Care ABA'.
[12] Neff, *'Weighted Vests, Autism, & Why and How to Use Them - Neurodivergent Insights'*.

who do, show a very positive reaction. One of her clients says she *"absolutely needs"* her weighted vest because it calms her down so well and *"she can feel herself way better"* with it. Overall, the positive effects Zajicek observes are reduction of state of arousal, muscle relaxation, improved bodily awareness and general relaxation. According to her, weighted wearables are indispensable for the ASD community.

I also consulted a psychologist who shared her positive experiences with pressure stimulation in individuals with ASD. She references the Squease™ vest, which is an inflatable pressure vest, stating that it helps stabilize the upper body and has an overall calming effect. In contrast to weighted vests, pressure vests *"can be inflated as desired"* and *"do not drag down"*.

10 Squease™. inflatable vest.

11 Squease™ hidden in a jacket.

In her article *'Calming Effects of Deep Touch Pressure in Patients with Autistic Disorder, College Students, and Animals'*, scientist Temple Grandin talks about oversensitivity and her invention of the "squeeze machine" or "hug machine". Having ASD herself, she writes of personal experiences of being overstimulated and finding a way to calm herself. The squeeze machine is a device in which an individual can lie down in on their stomach. The sides are covered with foam rubber and apply deep pressure stimulation. Important is that the user is completely in control of pressure intensity and duration. This being-in-control allowed Grandin to reduce oversensitivity by using the machine once or twice a day for 15 minutes. *"A once overwhelming stimulus was now a pleasurable experience."*[13]

With the *OTO hugging chair*, Alexia Audrain adopted the idea of the squeeze machine and integrated it into a new, non-stigmatising design. It is also primarily meant for people with ASD to aid as a calming sensation.[14]

12 Temple Grandin. Squease machine. 1992.

13 Alexia Audrain. OTO the hugging chair. 2019.

[13] Grandin, *'Calming Effects of Deep Touch Pressure in Patients with Autistic Disorder, College Students, and Animals'*.
[14] 'OTO Le Fauteuil à Étreindre Archives'.

Everyone, regardless of neurotype, can occasionally suffer from anxiety. A calming tactile wearable may therefore benefit a wide range of individuals and contribute to overall well-being.[15]

Weighted products such as therapy blankets, sleeping bags, eye masks, and lap pillows use deep pressure stimulation to promote relaxation and a sense of calm. These items can be incorporated into everyday routines or used in therapeutic settings. They are designed to be supportive for anyone seeking comfort, including but not limited to people with sensory processing differences.[16] For children who have difficulties focusing or experience sleep disturbances, a weighted stuffed animal may help them relax and feel more at ease.[17] There are also weighted products designed for babies, intended to support calmness and more restful sleep.[18]

14 Weighted collar for children.

15 Weighted robe for everyday life and travel

[15] Haynes et al., '*A Calming Hug*'.
[16] 'TherapieWelt.de - Produkte für besseren Schlaf, gegen Stress und Angst'.
[17] 'Die Vorteile von Kuscheltieren mit Gewicht'.
[18] 'BABYDEEPSLEEP® - Besserer Schlaf für die ganze Familie'.

State of the Art

Inflatables in design

To apply pressure to the body through a wearable, one can make use of the expanding properties of an inflating element. By using mostly air and minimal material, inflatable designs achieve a soft, lightweight character.

Hans Hemmert, for example, has made a large amount of balloon sculptures, some of which are adapted to the affiliated exhibition space, others are standalone. These balloons are made of latex and explore the tension between volume and weightlessness.[19]

Another project using airiness to its advantage is *Skum Pavilion* by BIG. Inspired by *"inflatable castles of childhood",* this pavilion is fully installed in seven minutes and offers shade for festival visitors.[20]

Floating above limits by SiiGii is a latex wearable designed to protect her from the sun, which she needs due to a sun allergy, and also functions as a floating device for relaxing in water. The artists states: *"Simply put, I could never lay on a pool float and relax in the sun. I had to become the float."*[21]

The inflated golden tubes by artist duo L/B create a comfortable and cosy atmosphere. They are nestled against the walls of a space and *"invite visitors to reimagine the familiar interiors."*[22]

In architecture and design, inflatables often entail a sense of comfort and protection, carrying a playful quality. These characteristics form the basis for the design concept of the wearable proposed in this thesis.

[19] 'Hans Hemmert's Yellow Blobs & Life-Sized Balloon Tank'.
[20] 'Skum Pavilion'.
[21] 'SiiGii | Official Site'.
[22] Foksal, 'Comfort #8'.


16 Hans Hemmert. Yellow Sculpture Fitting to Mona Standing. 1998.

17 SiiGii. Floating above limits. 2020.


18 L/B. Comfort #8. 2010.

19 BIG. Skum Pavilion. 2016.

Body architecture

In the Architectural Design issue *3D-printed body architecture,* architect, curator and writer Neil Leach mentions the *"history of exploring the relationship between the human body and architecture"* and proposes possible reasons why architects would benefit from designing wearables. It could be a medium to experiment with new technologies, a form of *'proto-architecture'* to explore ideas in smaller scale, or a completely novel genre of architectural design. Leach does not settle for one explanation but refers to many designers working with wearables who have some sort of background in architecture or have been working in collaboration with architects. Furthermore, he references architect Zaha Hadid, who emphasizes the fundamental importance of the relation to the human scale in both architecture and wearable design. He also cites architect Paola Antonelli, who argues that architecture and body architecture are both forms of design and, as such, should therefore not be distinguished based on differences in scale. However one might relate body architecture to architecture, it cannot be denied that both fields require similar design skills and rely strongly on digital technologies.[23]

This thesis proposes the design of a wearable because it serves as an effective method for investigating the sensory system, as it both interacts with and draws inspiration from the body's natural functions. Furthermore, to create a wearable, similar design tools to those used in conventional architectural practice are employed but augmented by advanced fabrication techniques.

[23] Leach, *'What Is 3D-Printed Body Architecture'.*

Lucy McRae and Bart Hess

The term *body architect* is shaped by designer and science-fiction artist Lucy McRae who uses it to convey the integration of the human body as central focus in her design work.[24] In her latest work, McRae explores how the body might transform and evolve, as technology increasingly shapes our lives.[25] However, in collaboration with artist Bart Hess, she already started working with the human body in her earlier work. In *Grow on you* they manipulated and *'deformed'* the human body by experimenting how random objects could be applied to it and questioning the *"ideals of beauty"*.[26]

20 LucyandBart. 2010.

21 LucyandBart. Germination day one. 2010.

[24] Leach, *'What Is 3D-Printed Body Architecture'*.
[25] 'Lucy McRae – World Renowned Sci Fi Artist and Body Architect'.
[26] 'Bart Hess | LucyandBart'.

Neri Oxman

Body architecture explores the relationship between the human body and architecture. As in conventional architecture, the focus lies on structure, materiality and function and relation to the human scale. Neri Oxman, a designer with a background in architecture, writes: *„[W]hen you design a wearable you are designing a very small building."* She further states that her designs *"emulate, amplify, augment, or 'reinterpret'"* the body system. *Anthozoa*, for example, is a 3D-printed garment inspired by the human skin and the appearance of barnacles. Varying in rigidity and flexibility, the printed elements are aligned to follow the shape of the body. *Mushtari* is inspired by the gastrointestinal tract and uses microbial cultures to generate energy. It is a 3D-printed *"artificial organ."* [27]

22 Neri Oxman and members of the Mediated Matter Group in collaboration with Stratasys and Iris van Herpen.Anthozoa. 2013.

23 Neri Oxman and members of the Mediated Matter Group in collaboration with Stratasys. Mushtari. 2015.

[27] Oxman, *'Dermi Domus - A Grown Wardrobe for Bodies and Building'*.

Behnaz Farahi

While Oxman's designs draw inspiration from the body itself, the designs by Behnaz Farahi - also a trained architect - tend to look outward. Her wearables explore bodily perception and social interaction, occasionally addressing feminist issues. The concept of the gaze or male gaze recurs throughout Farahi's work. With *Caress of the Gaze* she created a wearable that recognizes and responds to the gaze of onlookers, mimicking the skin's movement in reaction to emotional stimuli. *Opale* is another wearable which reacts to the facial expressions of surrounding people through an interactive pneumatic system, demonstrating our tendency to either reflect or counter the emotions directed at us.[28]

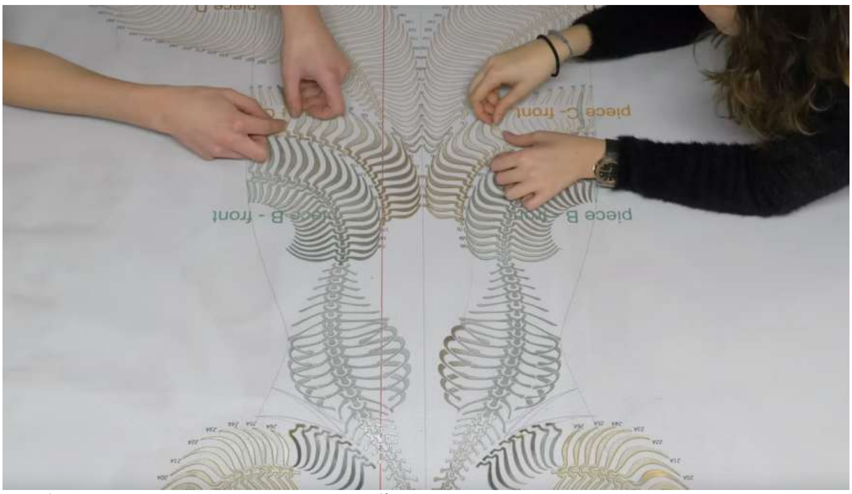
24 Behnaz Farahi. Caress of the Gaze. 2015.

25 Behnaz Farahi. Opale. 2017.

[28] 'Behnaz Farahi'.

Iris Van Herpen

Iris Van Herpen is an Haute Couture fashion designer whose design approach has been influenced by working with various architects.[29] She considers her designs as an *“interdisciplinary language”*, the product of mixing diverse fields such as *“art, chemistry, dance, physics, architecture, biology, design, and technology.”*[30] In her 2020 collection *Sensory Seas* she draws inspiration from the sensory interactions within the human body and their parallels in the delicate, fibrous forms of ocean life. The complex designs were created using the 3D modelling software *Rhinoceros 3D* in combination with the visual programming environment for computational design *Grasshopper 3D,* laser-cut, and then meticulously assembled and embellished by hand. Together, the layers form *“vibrant coral textures that expand and contract around the body.”*[31]



26 Iris Van Herpen. Sensory Seas. Process Film. 2020.

[29] Kartika, *‘Wearable Architecture’*.
[30] ‘Iris van Herpen, Exhibition, Sculpting the Senses’.
[31] ‘Sensory Seas | Haute Couture’.

27 Iris Van Herpen.Sensory Seas.Look 12. 2020.

28 Iris Van Herpen.Sensory Seas.Look 19. 2020.

29 Iris Van Herpen.Sensory Seas.Look 15. 2020.

3D-printed biomaterials

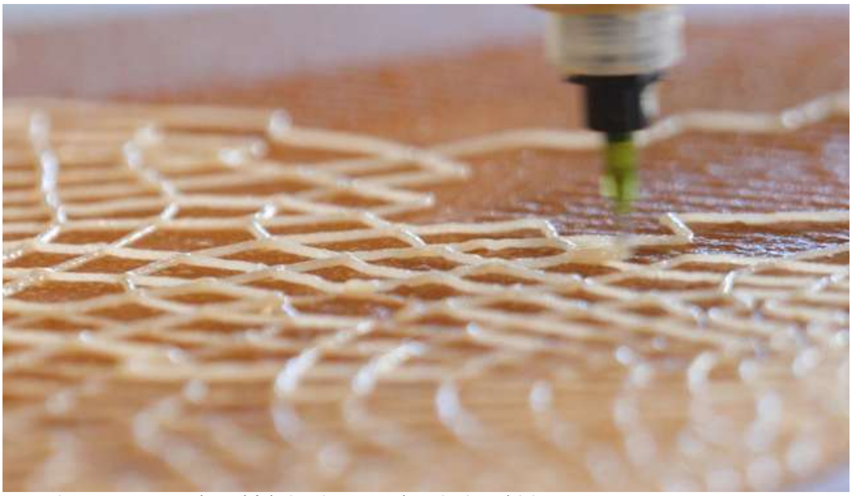
Water-based biocomposites by Neri Oxman

The need to replace fuel-based products, combined with advancements in robotic fabrication, provides a foundation for exploring biocompatible materials. Neri Oxman and her research team have been exploring water-based composites in architectural scale structures, questioning the composition of homogeneous elements in our built environment, and aiming for more complex *„structural hierarchy and material composition"* – as are observed in nature. Shifting the shape-giving properties to the material itself.[32]

The biopolymer pavilion *Aguahoja* is a structural example consisting of 3D-printed biopolymer composites. Its layered network of patterns – bio-composite – gives structural integrity. Natural decay is part of the design, as the material is supposed to *"return to the earth, for purposes of fueling new growth."* [33]

30 Neri Oxman. Aguahoja. 2019.

[32] 'Water-Based Fabrication'.
[33] 'Aguahoja'.

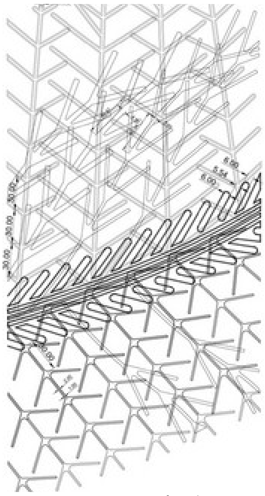


31 Neri Oxman. Water-based fabrication. Nozzle printing chitin pattern.

32 Neri Oxman. Water-based fabrication. Close-up of chitosan sample 13.

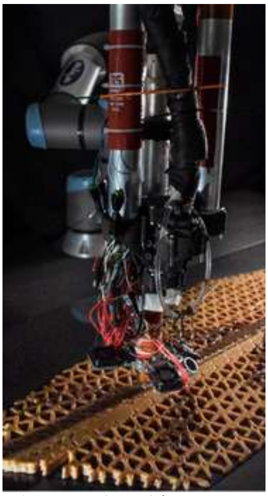
Waste-stream based biopolymers for architecture by CITA

The biogenic design research unit at CITA (Centre for Information Technology and Architecture in Copenhagen) explores how renewable materials and circular design strategies can be applied in architecture. *Radicant*, as part of a broader research project, exemplifies how waste-stream based biopolymers can be used for architectural elements. The material consists of a by-product of the meat industry – bone glue – and additional plant-based waste products. Computational tools and additive manufacturing techniques allow for control over the material's complexity. The design takes the form of a wall panelling with a gradually varying material composition. During the 3D printing process, the material mix can be adjusted to achieve the desired properties. The filigree pattern allows the water to evaporate evenly, helping the structure to retain its shape during the drying process.[34]



33 CITA. Generated print path. 2023.

34 CITA. Biomaterial test with recycled cotton. 2023.



35 CITA. Print with seagrass and bark fibrous. 2023.

[34] Nicholas et al., *Biopolymer Composites in Circular Design: Malleable Materials for an Instable Architecture.*


36 CITA. Radicant. 2023.

Design

Materiality

Architectural structures, wearables, pressure vests, and inflatables are unified by common purposes: to provide protection, comfort, and aesthetic value. This thesis describes the design of a comforting wearable, which additionally serves as a protective layer situated in the peripersonal space. By introducing pressure through inflation, it brings awareness to the sense of touch – or more precisely, the tactile sense – without the need for movement.

Designing for the immediate space surrounding the body with the intention of creating a tactile experience, an emphasis is placed on using natural materials. In contrast to synthetic materials, using bio-based materials is not only environmentally beneficial but also well-suited for creating designs relating to and extending the human body. A commonly used technique in body architecture fabrication is additive manufacturing allowing to create complex geometry using a wide range of materials. Due to their complexity, bio-based materials are often processed using computational and robotic tools. The process of 3D printing mimics the growth of natural structures as the material is applied in layers but fuses into a consistent object. Often, natural geometries are used as inspirations for the digital design of such objects or wearables. Unlike in traditional clothing design, pieces can be created as one and do not need seams. However, new limits and challenges of design are introduced such as the size of the 3D printer or the connection of pieces.[35]

The design process contains material studies of self-made bio-based materials, exploring various ingredients and ratios, showing different material property outcomes. The aim is to create a bio-based material whose properties allow it to be robotically 3D-printed.

[35] Koemer, *'Digitally Crafted Couture'*.

For the inflatable elements, latex is used. This is a natural product found as a milky fluid in 10% of flowering plants – most importantly the rubber tree. It is harvested by 'tapping' the tree and collecting the liquid in vessels. Natural latex rubber, as it is also called, shows highly elastic and durable properties, and is used for products like latex gloves, condoms or balloons. These products are created by dipping a mould into the liquid. This technique results in very thin objects. Latex is also used for various types of clothing. These items are mostly created with sheeted latex which is cut out and glued together at the seams. Due to its tightness, latex creates a 'second skin' effect.[36,37]

Its elasticity makes it particularly suitable for inflatable objects. When worn, the inflatable element facilitates sensory awareness by gradually altering its shape – from deflated to inflated. This transition acts as an 'interruption' in the user's current state, heightening the sense of bodily awareness.

[36] 'Latex'.
[37] 'Natural Rubber'.

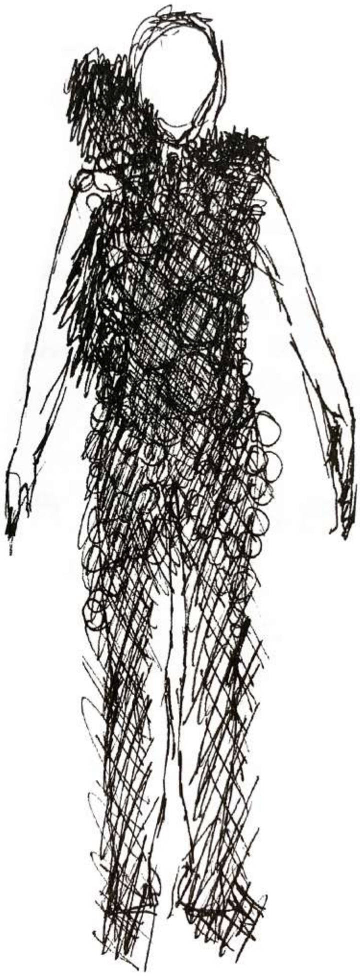
Concept

Combining the ideas of the inherently protective essence of a wearable and the easiness and happy nature of an inflatable the aim is to bring comfort through a tactile experience. Comfort is *"a state of physical ease and freedom from pain or constraint."* [38] Contrary to the claim, that awareness of the sense of touch is achieved through limits and interferences, which have a negative connotation, this design enhances awareness through targeting a positive feeling.

This said effect is achieved by simulating a universally known tactile experience – the hug. Hugging and being hugged is proven to relieve stress and anxiety, reduce heart rate and increase oxytocin (a hormone important for interpersonal bonding and positive emotions).[39] Deep pressure touch in the form of a hug, as stated in a previous chapter, can lead to a sense of safety, comfort, and ease. But for people with sensory sensitivity hugging can present difficulties. Sociability plays another important role. Lack of self-esteem and self-confidence can *"de-crease the likelihood of taking the initiative to hug."* [40]

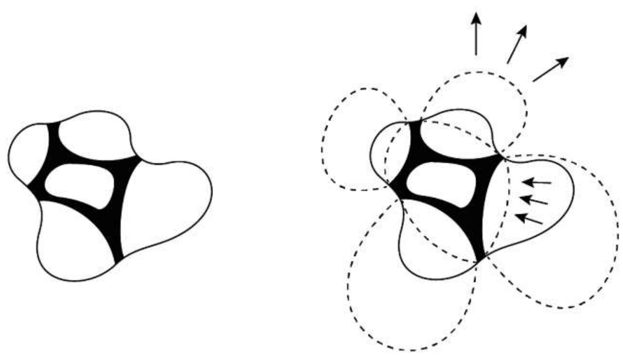
The objective of this wearable is to give the same soothing sensation as a hug to anybody regardless of sociability and tactile sensitivity. Targeting corresponding areas of the body which are touched during a hug and allowing the wearer full control of duration and intensity. The ability to remain in control enhances the user's sense of safety and comfort. To ensure accessibility for a broad range of users, the design considers adaptability to different body sizes.

[38] Oxford Languages, 'Comfort'.
[39] Haynes et al., *'A Calming Hug'*.
[40] Forsell and Åström, *'Meanings of Hugging'*.

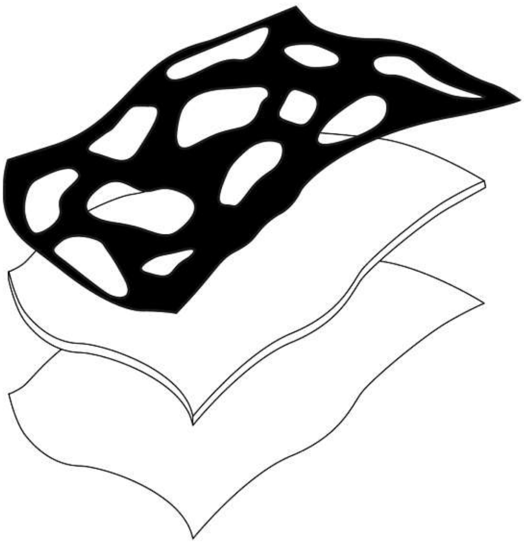


To imitate the pressure of a hug, the feature inflation is used. Encaged in a rigid structure, an inflatable can only expand at openings. Making use of this logic, the design contains a holey element whose density and structure define the location and intensity of inflation. Since the holes correspond to a previously made hug pressure map, the wearable is enabled to simulate a hug.

The idea for the design's structure arose while looking at an image of soap foam. When looking closely, in areas where two bubbles meet, it seems like they are held in place by tiny strings. As if it was not an accumulation of many small bubbles, but one big bubble with a cohesive net. To embody this concept, the design incorporates a layered structural system. The innermost layer, which is touching the skin, is said rigid structure with holes, in the middle there is an inflatable and all of it is covered by a shell.



hold shape *reshape*



As air is pumped into the inflatable, it can only expand in the areas where holes are located. Since the holes are oriented towards the wearer the inflatable starts to apply pressure to the body. The outer shell prevents inflation in the other direction and is used as a structural support for the overall design.

The design workflow combines analogue and digital methods. Starting out with a physical hug map which is then applied onto a digital model to serve as a base for the designs shape. The structure is then further processed in *Grasshopper 3D* using colour information as the main parameter. This converts the colours of the hug map into a perforated structure, creating larger holes in the areas with the highest pressure of the initial hug.

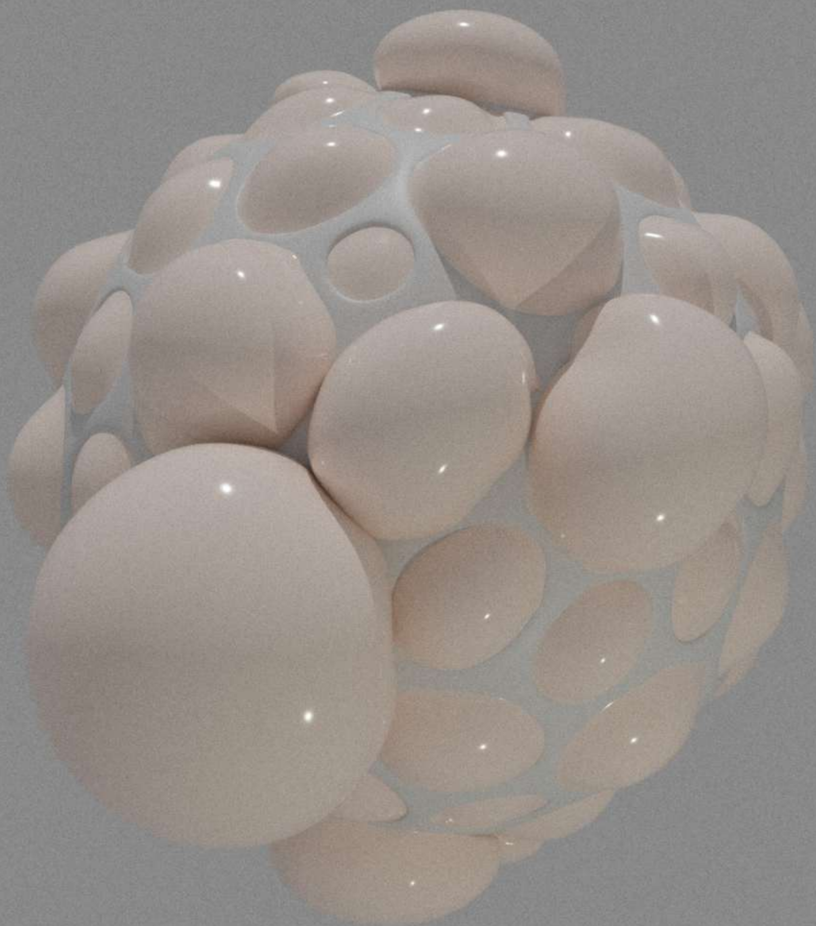
Concept trial

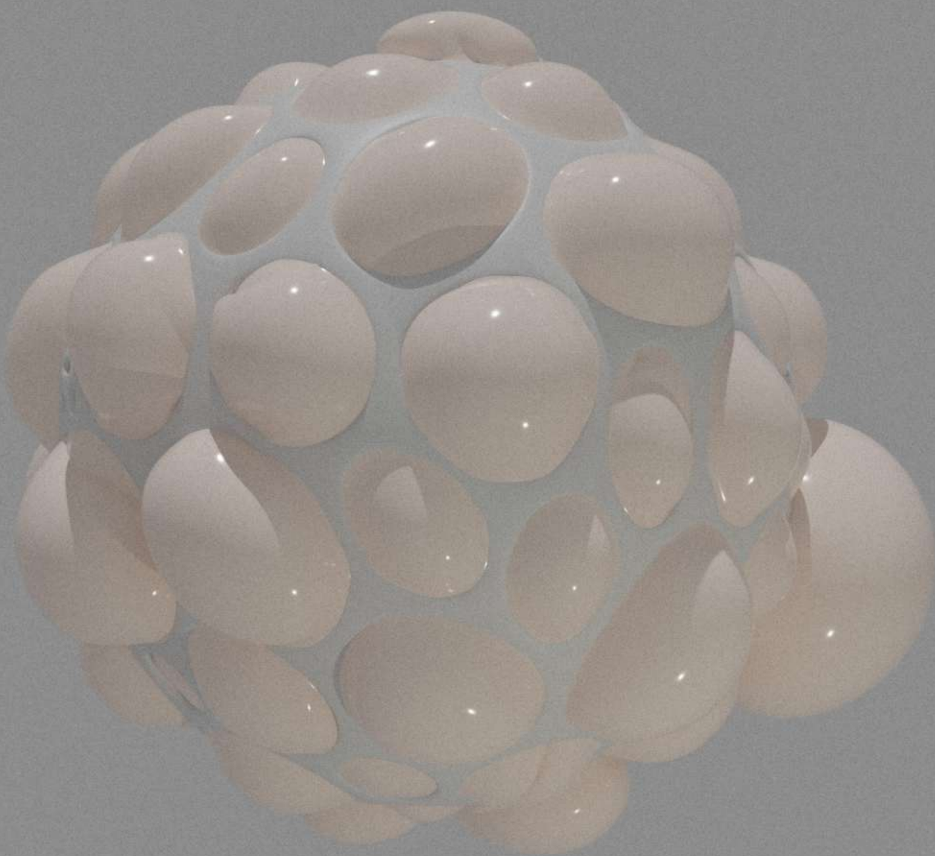

inflatable. softness and lightness


latex. strength and tension

inflatable with constraint. defining shape

Concept simulation





Design workflow

Hug map creation

To create the hug map, a person was covered with blue fingerpaint and then proceeded to hug another person wearing white clothing. Performing the classic hug in which the right arm reaches over the left shoulder and the left arm goes under the right arm of the other person. Each person touches the back of the other with both hands. The chests are touching, and the heads are side by side. The imprint left on the second person shows the areas which touch during a hug. The amount of pressure felt on the body is reflected in a slight colour gradient.

One aspect that is noticed though this map is that this specific hug mostly affects the upper body - more precisely the chest, areas of the stomach, back, shoulders and face, as well as the lower arms and hands. As this design imitates the passive

37-40


41


42

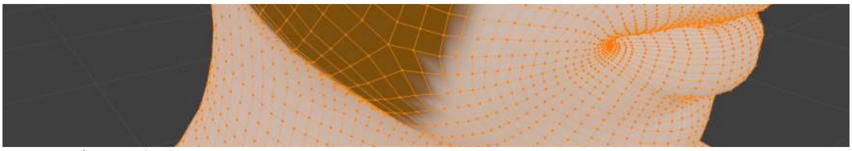
experience of being hugged, it focuses on the front and back of the torso and the face. It does not include the arms as they are only touched when being the active hugger.

For this project only one hug map was created, representing the touching area of two specific people during a classic hug. This could be tested further as the touching area varies according to body shape and size and hugging style.

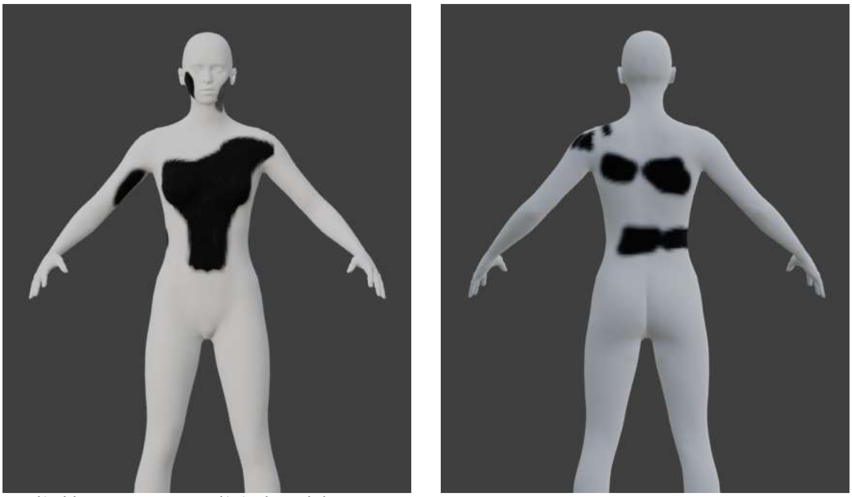
Vertex colour painting

The next step was to digitalize the hug pressure map to enable working with it further. With the application *makehuman* two different sized digital human models were created and then imported to *Blender*. Using photos of the analogue hug map as a template, the map was transferred onto the digital models using *vertex colour painting*. This method allows colour values to be assigned directly to the vertices of a mesh by using a digital brush – just like painting.

The result is a mesh whose vertices each have their own specific colour value which serve as the main input parameter for the following computational workflow. Moreover, the painted human models serve as an orientation for designing the overall shape of the wearable as they clearly show which areas are impacted during a hug.



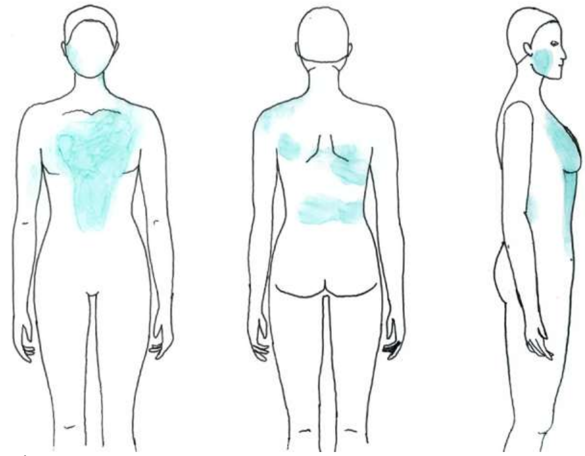
vertex colour painting



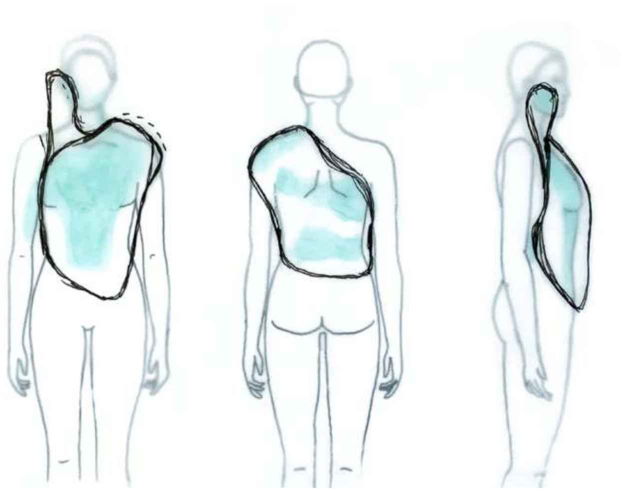
applied hug map on one digital model

Designing overall shape

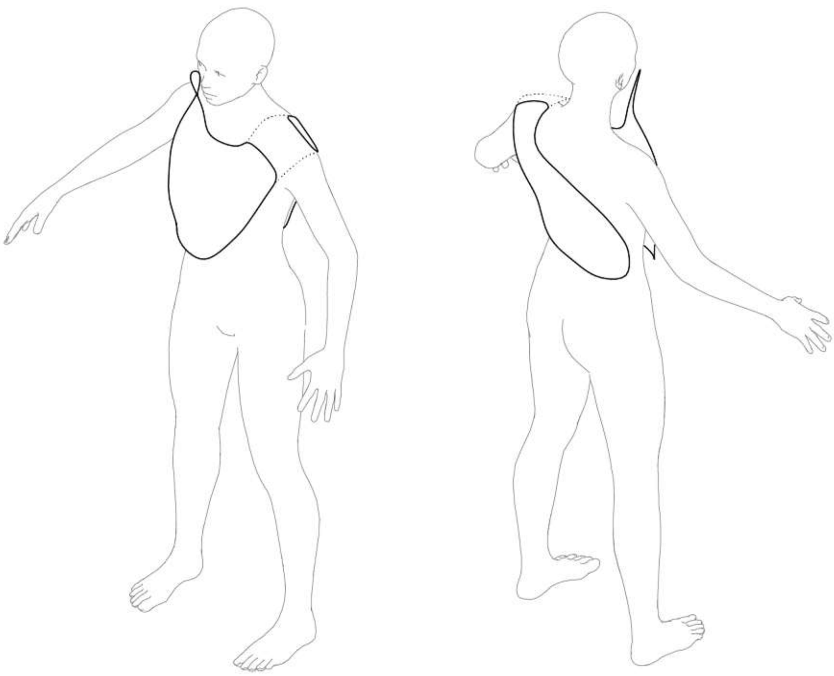
As stated in a previous chapter, the design focus lies on the upper body and parts of the face. A first sketch captured the hug map and roughly followed the shape of the body and was then 3D-modelled using Blender. For further adapting the shape, it was necessary to go back and forth between sketching and digitally shaping and adjusting.



hug map sketch

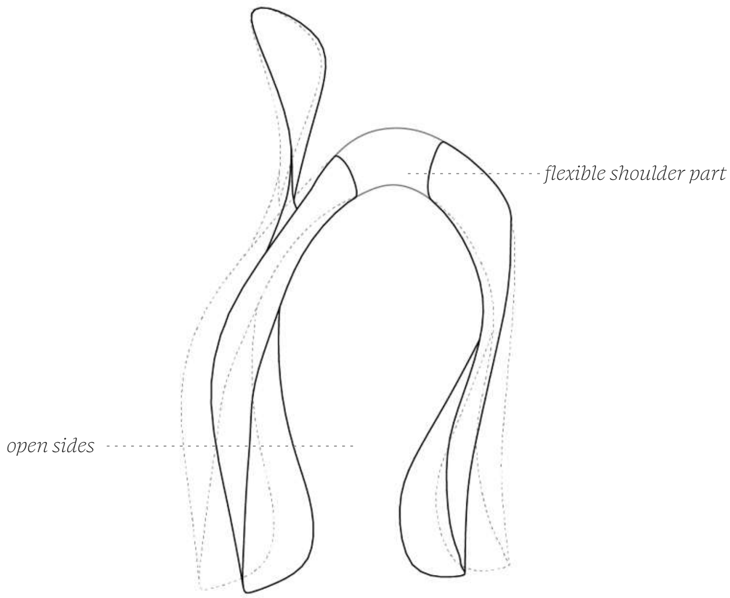


shape sketch



final base shape

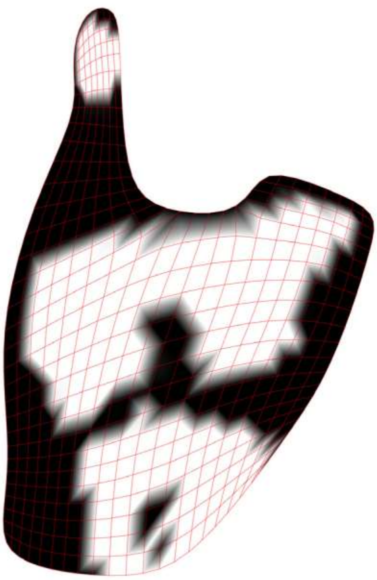
Adaptability to different body shapes and sizes was one key design objective that needed to be ensured during this step. Keeping the design open on both sides of the body and only closing the shape over one shoulder allows space for adaption. The shoulder part is planned to be made from a flexible material to further ensure this. Which leaves two rigid shapes: one on the front and the other in the back of the upper body.



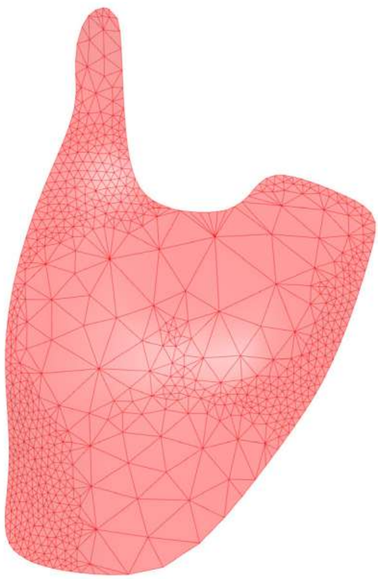
adaptability to body size

Computational workflow

By vertex colour painting, the colours of the hug map were applied to the finalized base shapes. To transfer the models to *Rhinoceros 3D* the file format FBX was used because it includes vertex colour information. With *Grasshopper 3D* the colour information is extracted and used to 'remesh' the shape by colour value. An addon allows to recreate a mesh and correlating its resolution according to colour information stored in the vertices. In this case, white areas result in a lower mesh resolution, while black areas produce a higher resolution. Next, the dual mesh is generated by converting each face of the original mesh into a vertex. If two faces previously shared an edge, their corresponding dual points are now connected by an edge. Therefore, the connectivity of the mesh is preserved but the roles of vertices and edges are flipped.[41]



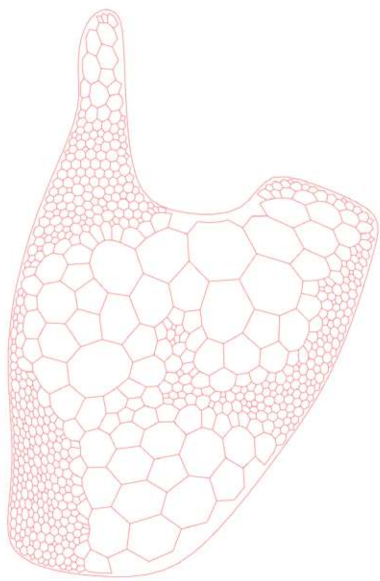
1. imported coloured mesh



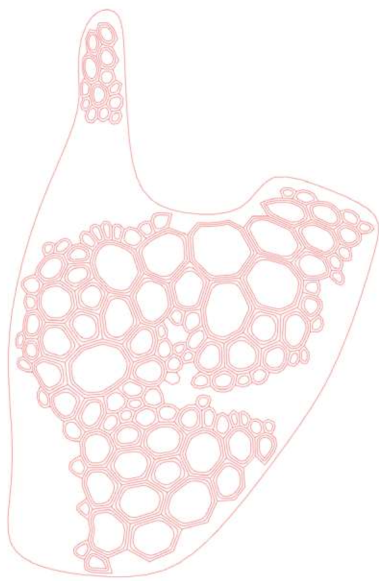
2. remesh by colour

[41] Taubin, *'Dual Mesh Resampling'*.

The result is a honeycomb-like pattern whose hole sizes match the original colour map. The most important parameters in this workflow are the 'Length Interval' and 'Iterations' of the 'Remesh by Colour' step which ultimately define the holes sizes. For the final design, these values were adjusted after testing the hole sizes with prototypes. In the last step the smallest circles up to a specific size are removed to create solid areas. This helps to make the overall structure stronger and prevents fabrication difficulties.

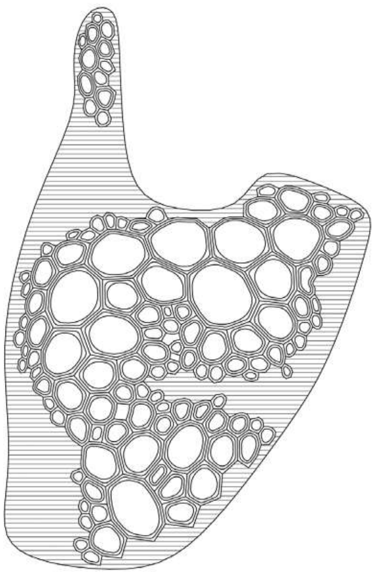


3. dual mesh

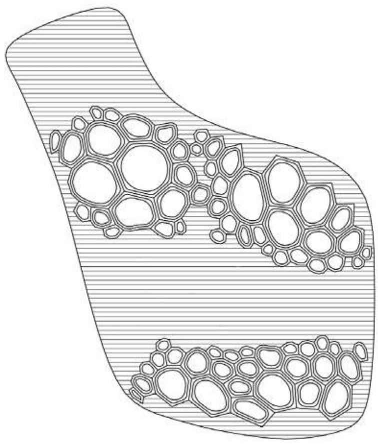


4. cull small holes

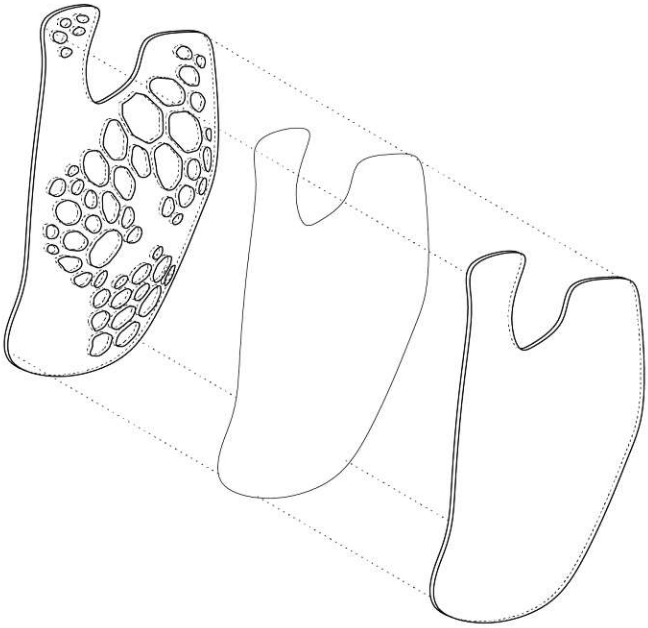
The final design of the front and back part of the wearable consists of three layers each. Closest to the body is the computed element, followed by the inflatable and covered with an external shell. Both the inner and outer element are made from a rigid material encaging the flexible inflatable. The layers are joined with book screws.



printing path front

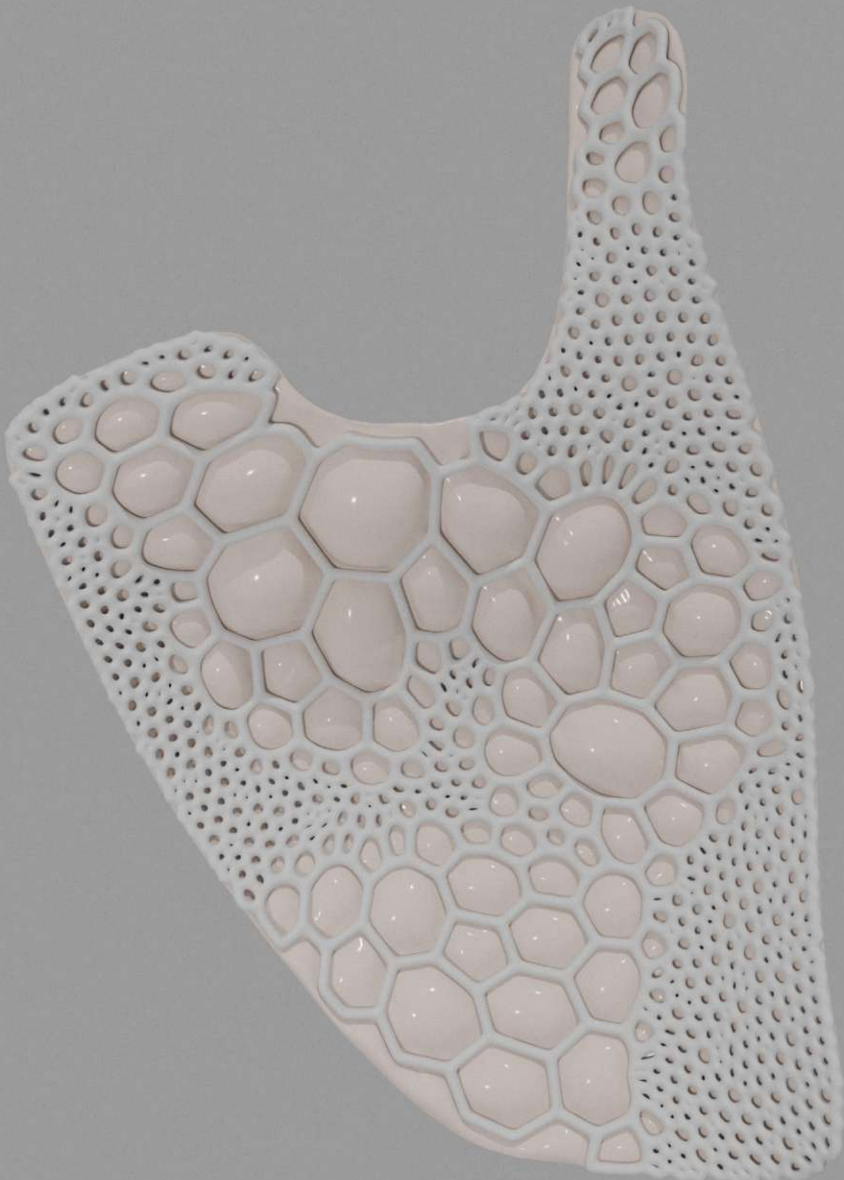


printing path back

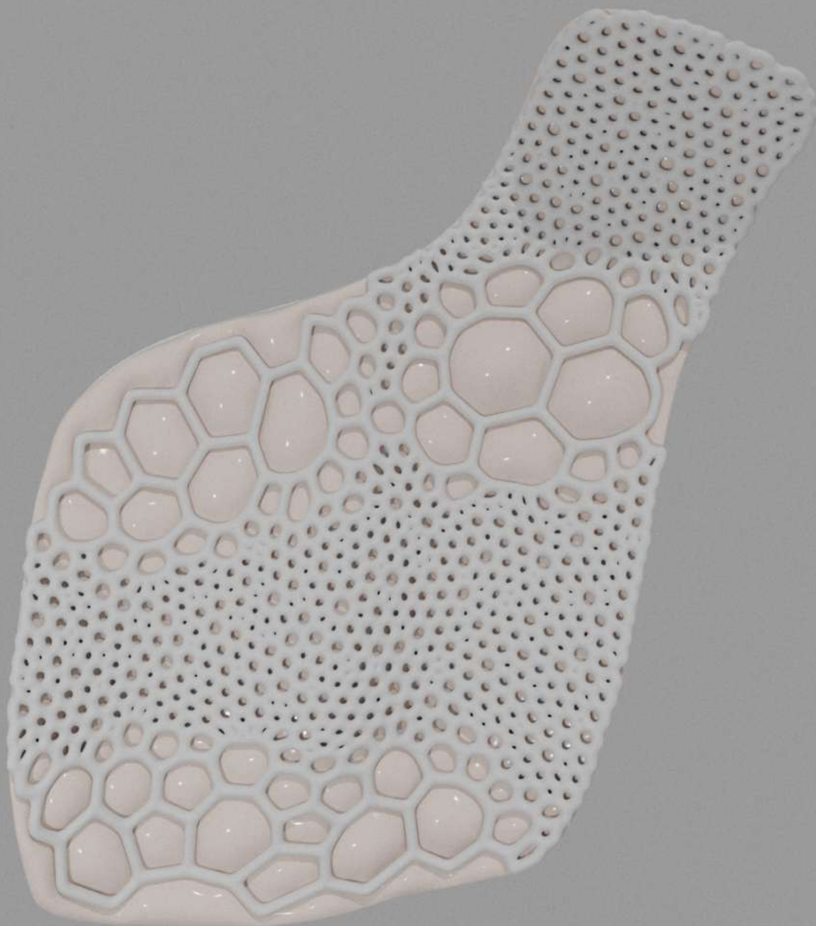


holey element inflatable shell

Two air pumps with air release valves allow the wearer to inflate the wearable and still be in control of intensity. These pumps are connected to the inflatable through silicone tubes. The same tubes are used to connect the wearable on both sides of the body. Cord stoppers allow to adjust the length according to body size of the wearer. The only element that extends over the shoulder is the inflatable joined to one layer, connecting the front and back with each other and keeping this part flexible.



design without hole culling. front



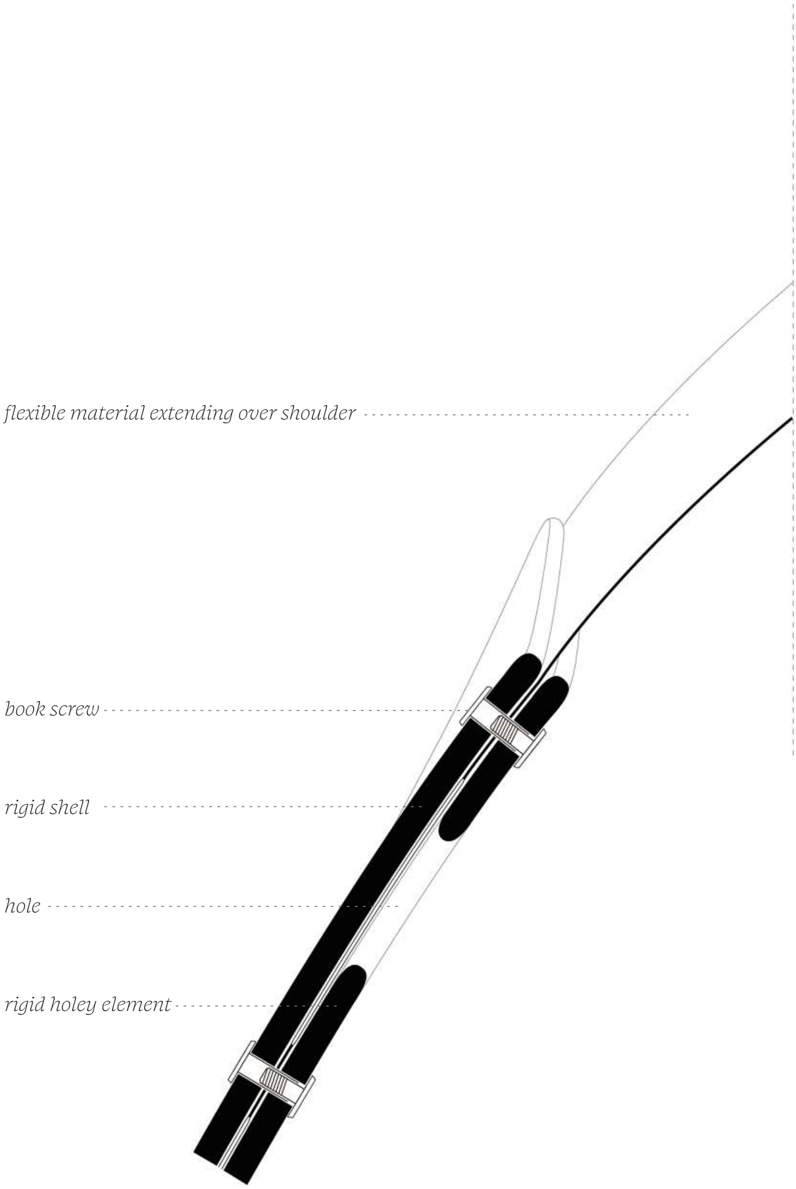
design without hole culling. back

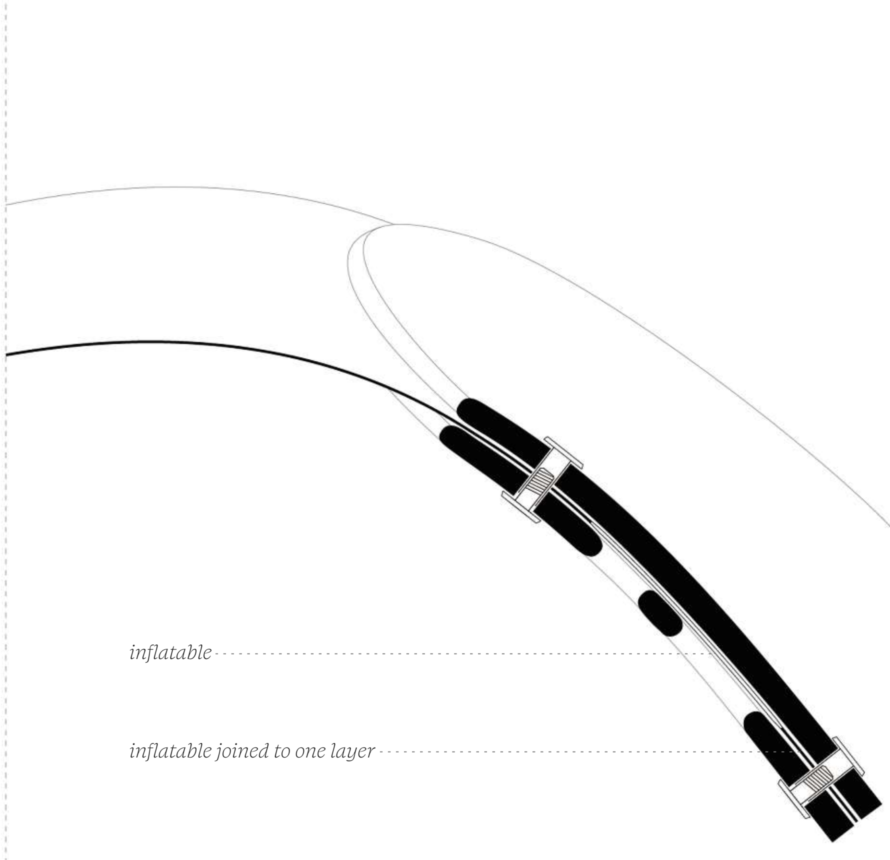
Final wearable design

design. front

design. back

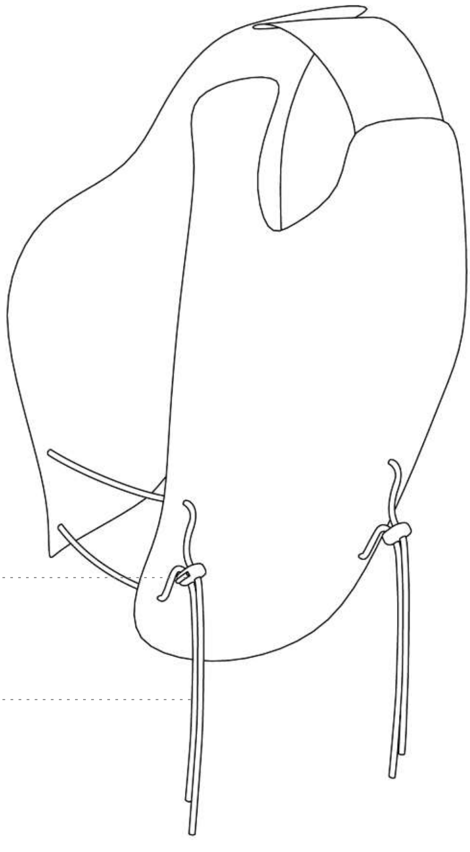
Shoulder and layer connections



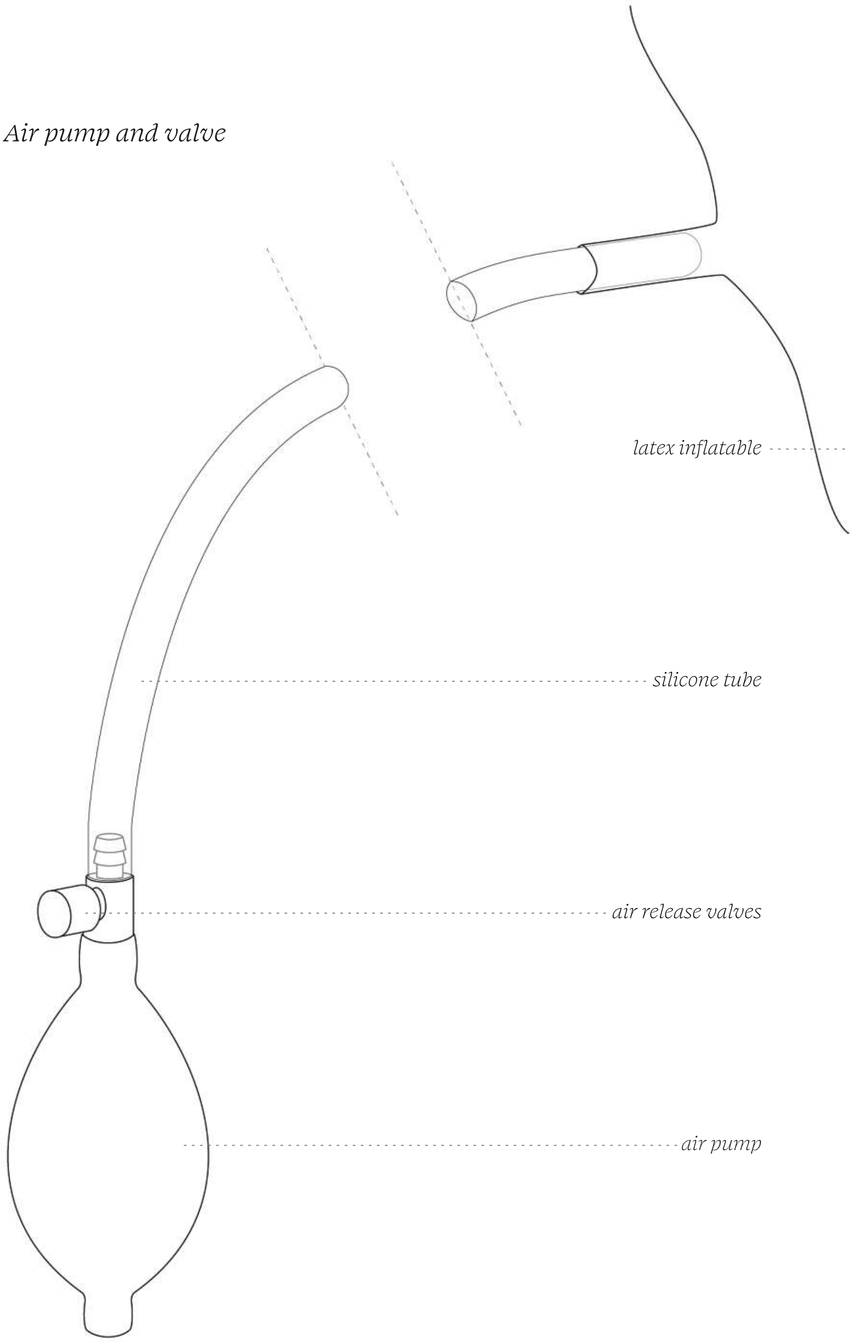


Two layers of latex form the inflatable, joined at the edges of the design to create an airtight element. In areas where all layers are connected with book screws, the inflatable is also fused into a single layer to allow penetration without air leakage. The shoulder extension is made from a thicker layer of latex to ensure its durability.

Closure on the sides



Air pump and valve



Material studies

The increased focus on bio-based materials in design is an attempt to making products more sustainable. New materials are created by using ingredients that partly have been considered waste – for example, by-products of the food industry. The goal of creating such materials and products is a *"circular society"* – reducing the need for non-biodegradable materials that keep ending up in nature damaging natural systems.[42]

Creating a bioplastic usually requires three to five ingredients: biopolymers, bio-plasticizers, a solvent and sometimes bio-additives. Since the ingredients are *"renewable biomass sources"* they are all biodegradable.[43]

The amount of possible ingredients that can be used entails a large number of combinations and mixing ratios, and therefore material properties. During a workshop at the Dessau Department of Design students explored the formstability of various mixtures by robotically printing test pieces. The factors which were evaluated were *"strength, shrinkage, durability, cracking, color loss, curing time, [...] additive energy sources (heating, cooling, and UV), viscosity, stickiness, workability, and processability."*[44] These are also the properties considered in the material studies of this thesis.

[42] Rodríguez, '*Biomaterials 101: From Organic Waste to Material Gold – Fab Lab*
[43] Barcelona | Research, Education, Innovation Centre. '3D Printing Bioplastics - Materiability'.
[44] Ibid.

Biopolymer		*Bio-plasticizer*		*Solvent*
Starch	+	Glycerin	+	Water
Agar Agar		Sorbitol		Vinegar
Gelatine				
Xanthan Gum				

+

Bio-additives	Wood flour	Cotton
	Hemp wool	Eggshells
	Paper Pulp	Seagrass
	Coffee grounds	etc.

components of bio-based materials

Desired properties

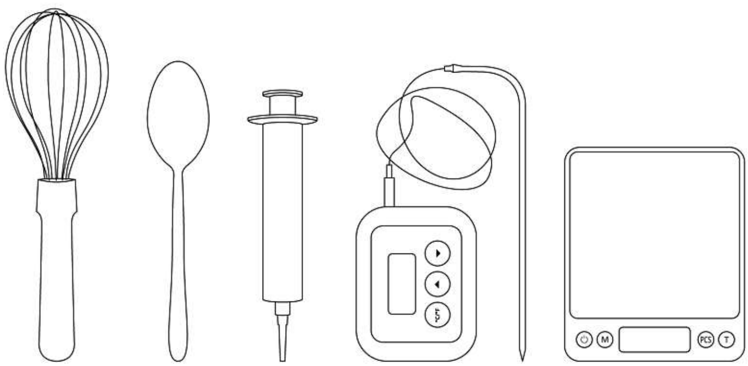
In this project, the bio-based material is used to create the inner and outer elements of the design. Therefore, it needs to be able to withstand the force of inflation and be rigid and non-flexible. Many existing recipes achieve flexible or brittle bioplastics. The challenge of theses material studies is to adjust ingredients and ratios to create a strong material. Furthermore, it is desired that the material can be used for robotic 3D printing. Meaning, that it should be liquid enough to be extruded and layers fuse together into one consistent object, but not too liquid, as the material should stay in place when printed. Moreover, as the material dries, shrinkage should remain minimal which often is a challenge with bio-based materials.

Material development

Process and testing setup

The approach to finding a good material was as follows: First, basic recipes from various sources were tested to find the most suitable for this project. The mixtures were then further developed by repeatedly changing factors responsible for the outcome properties to ultimately achieve the desired material properties.

All test materials were first mixed, then cooked and finally manually extruded - the process thoroughly documented throughout. For mixing and cooking, a conventional cooking pot was used, and a precision scale ensured accurate measurement of the ingredients. To avoid clumps, powdered ingredients were carefully stirred in with a whisk, while a simple spoon was used for stirring during the heating process. A thermostat was frequently employed to monitor the temperature. The warm material was then drawn up with a syringe and manually printed onto plastic sheets to simulate the robotic printing process. The two best results were further used to create various prototypes and to test additives.



utensils

Property factors

Ingredients	*Cooking*	*Result*
* choice	* temperature	* shrinkage
* ratio	* time	* toughness
* temperature	* cool down time	* rigidity
Mixing	*Printing*	
* order	* material temperature	
* temperature	* nozzle size	
* time	* speed	
* tool	* air pressure	

Process for best results

The final mixing process that brought the best results began by mixing all materials in a specific order – first water, then the powdered ingredients and finally glycerine – while still cold. The mixture was then cooked for around eight to ten minutes over low heat, continuously stirring, and ensuring that the mixture does not exceed 55-60°C to prevent any evaporation or burning. For optimal application properties, the material was cooled to around 35°C-45°C before being applied with the syringe. At this temperature, the material is liquid enough to be extruded and fuse into a single object, yet stable enough to retain its shape without melting. It should not fall below 30°C, as this is when the material begins to slowly harden. The nozzle size used for printing depends on the composition of the mixture. Without additives, very small nozzles are possible; for testing, 2mm and 4mm diameters were selected. However, once additives were added, only the 4mm nozzle worked, as smaller ones clogged immediately. Drying took approximately one week at room temperature for each test.

Initial tests: basic mixtures

To narrow down possibilities, the initial material tests focused on two basic mixtures without additives: one starch-based and the other gelatine-based. A third option, using plant-based agar agar instead of the animal-derived gelatine, was ruled out early on, due to its high likelihood of shrinkage.[45]

recipe 0.1

Biopolymer		*Bio-plasticizer*		*Solvent*
Starch	+	Glycerin	+	Water Vinegar

recipe 0.2

Biopolymer		*Bio-plasticizer*		*Solvent*
Gelatine	+	Glycerin	+	Water

There exist already a lot of recipes for DIY bioplastics. For this study three main sources were used as a starting point. *"Bioplastic Cook Book"* by Margaret Dunne[46], *"Recipes for Material Activism"* by Miriam Ribul[47] and *"Printing with Biofoams – Transient futures exploration"* by Claudia Palcova.[48]

Even though the properties of the starch-based material allowed it to be extruded, the high level of shrinkage during drying caused it to break. The result was a weak and slightly flexible material. With the gelatine-based mixture, it was the opposite: it was far too liquid to be extruded and was therefore simply poured onto plastic foil. Once dried, the material felt very strong but also slightly flexible.

[45] Dunne, *Bioplastic Cook Book.*
[46] Ibid.
[47] Ribul, *Recipes for Material Activism.*
[48] Palcova, *Printing with Biofoams.*

O.1.1

O.1.2

O.1.3 + agar agar

O.2

material studies

Refining recipes

As the initial tests did not yield the desired properties, a second biopolymer – xanthan gum – was utilized to increase rigidity and strength of the material. Xanthan gum has thickening, stabilizing, and emulsifying properties, and is often used as a food additive. Although xanthan gum is *"not readily biodegradable"* it does degrade after some time. Therefore, it has no negative impact on the final materials biodegradability, especially since only a small amount of it is used.[49]

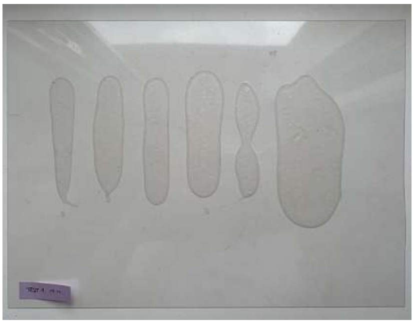
Applied to the material tests, some of the starch or gelatine, depending on the recipe, was replaced by xanthan gum. It quickly became apparent that using gelatine and xanthan gum together works well. The results were more durable and stronger than before, with a white, foamy appearance. This combination of ingredients was further explored by varying the amount of gelatine and xanthan gum relative to water and glycerine in a series of additional tests.

Test 5 and Test 13 were the most successful, showing suitable viscosity for printing purposes after cooking, a minimal shrinkage during drying, and strong, rigid properties when dry. These recipes were used to produce prototypes resembling the pattern of the final design and further tests with a bio-additive.

On the following pages, the recipes and extruded tests are presented. The ingredients are listed in the order they were mixed.

[49] Kaidaniuk, Tertychniy, and Drazhnikova, *'Xanthan Gum as a Component of Starch-Based Bioplastic'.*

Tests: Starch and xanthan gum



Test 1

Water	80ml
Starch	1,6g
Xanthan gum	0,4g
Vinegar	15ml
Glycerine	5g

Test 2

Water	50ml
Starch	3g
Xanthan gum	5g
Vinegar	10ml
Glycerine	2,5g

Test 3

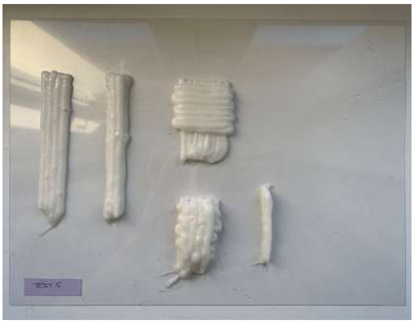
Water	50ml
Starch	3g
Xanthan gum	3g
Vinegar	10ml
Glycerine	1,5g

material studies

Tests: Gelatine and Xanthan gum

Test 4

Water	60ml
Gelatine	6g
Xanthan gum	2,5g
Glycerine	3g

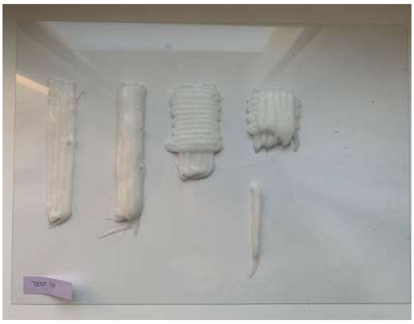


Test 5

Water	60ml
Gelatine	10g
Xanthan gum	1,5g
Glycerine	3g

Test 7

Water	60ml
Gelatine	4g
Xanthan gum	1,25g
Glycerine	3g



Test 10

Water	60ml
Gelatine	3g
Xanthan gum	2,8g
Glycerine	3g

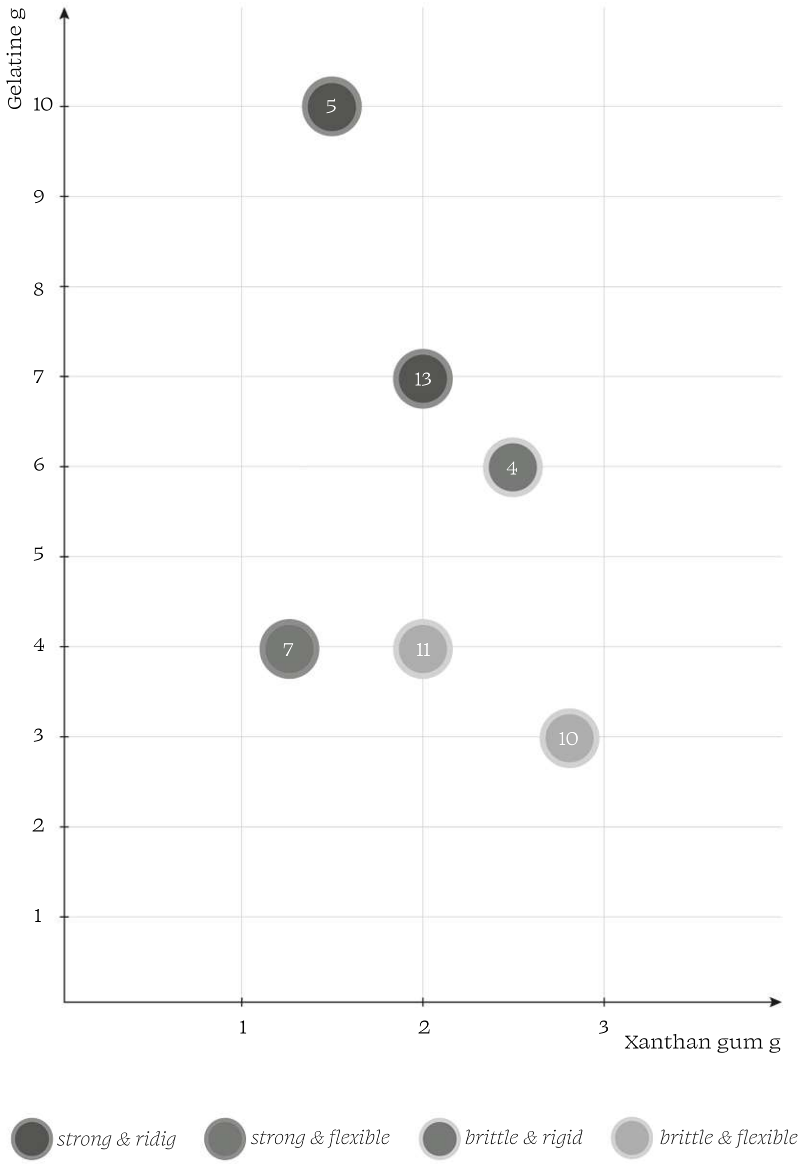
Test 11

Water	60ml
Gelatine	4g
Xanthan gum	2g
Glycerine	3g

Test 13

Water	60ml
Gelatine	7g
Xanthan gum	2g
Glycerine	3g

Qualitative material property results: gelatine-xanthan gum mixtures



Test 5 after printing

Test 5 dry

Test 13 dry

Bio - additive: wood flour

Once a suitable base mixture was found, the strength of the material could further be enhanced by incorporating additives. It was decided to use wood flour, as it is possible to easily produce it oneself, allowing control over its fineness. This is important to ensure that the material does not become too clumpy to be extruded through a nozzle.

To produce wood flour, branches of various bushes were either cut down or collected from the ground and then chopped into smaller pieces. These were then shredded using a coffee bean grinder and further on sieved. This process took some time, but the result was a well-suited additive for biomaterials. Depending on the type of wood, the fibers in the wood flour varied in length.

1. cutting

2. grinding

3. sieving

4. wood flour result

To understand how much wood flour is needed to achieve a strengthening effect, two tests were made using Mixture 13 as a base mix. In the first test, approximately 8% of wood flour (based on total weight) was added; in the second, around 4%. Both mixtures were still extrudable through the 4mm nozzle but immediately clogged smaller ones. The dried tests are very sturdy, with the first being slightly more rigid, though not showing a significant difference compared to the second.

wood flour

mixture 13 + 8,26 % wood flour

dry

mixture 13 + 3,85 % wood flour

dry

Material mixing process

1. Add cold water to pot.

2. Add gelatine to water. Let sit for ~5 minutes.

3. Slowly mix in xanthan gum with a whisk to prevent clumping.

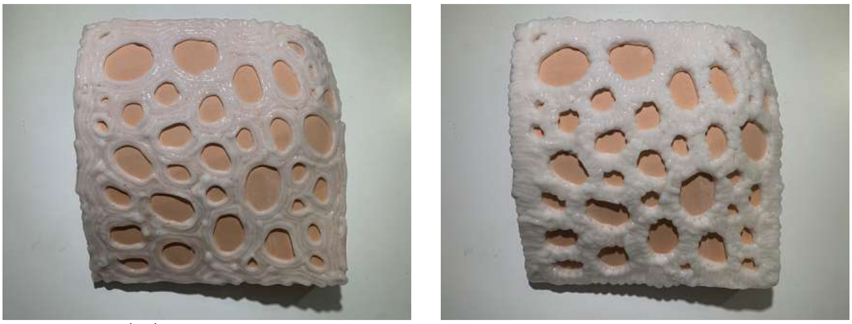
4. Add glycerin.

5. Cook on low heat for ~8 minutes while stirring continuously. The temperature should not exceed 50°C.

6. Take off heat and mix in additive - wood flour.

7 Material ready for application at ~40-45°C.

Prototypes



prototype 1. printing process

prototype 1. mixture 13. dry

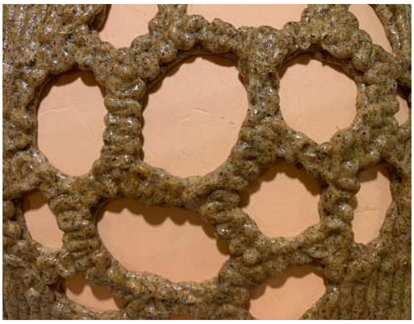
To test the material with the wearable's concept, two prototypes were created. A section of the front design was digitally cut out, and its negative mould was milled. The printing process was simulated manually, and the latex inflatable was also created manually. From the first prototype – produced without an additive – several learnings were gained.

First, the holes needed to be larger to allow the latex element to inflate properly. Second, two layers with a 2mm nozzle did not provide sufficient structural strength. As a result, the second

shell prototype with cotton mesh

latex inflatable

book screw connection

prototype 2. printing process

prototype 2. mixture 13 + 7,7% wood flour. dry

prototype used two layers with a 4mm nozzle and included an additive. The layers in both prototypes were printed perpendicular to each other to further improve material stability. Furthermore, the latex layer that expands through the holes was now much thinner, and the other layer that should not expand much thicker. These adjustments successfully achieved the desired outcome.

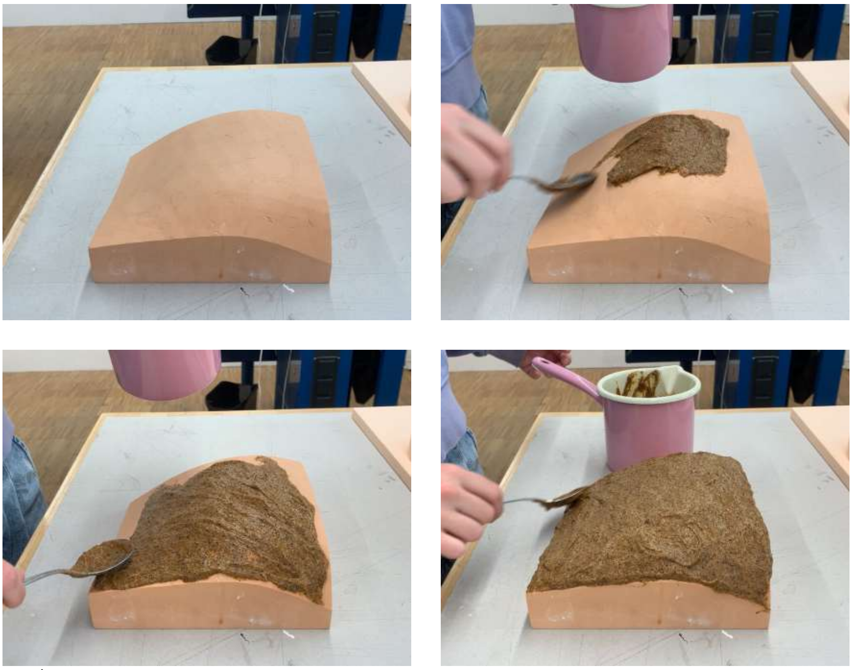
book screw connection

air inlet detail

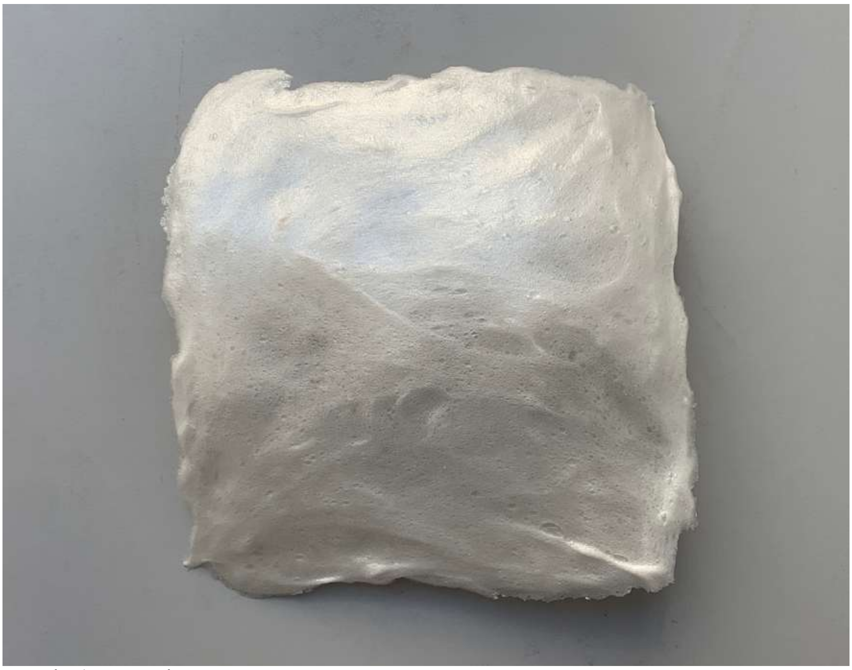
prototype 2. inflated

Casting biomaterial

Since one element of the design is solid, the idea was to try casting the material instead of printing it. This was attempted by spreading a thick layer directly onto the mould with a spoon. While this method is much faster than printing, it was more difficult to control thickness and keep it even. The dry result also turned out thin and brittle. Therefore, it was decided to print the solid elements as well, since the printed results showed much stronger properties.



casting process

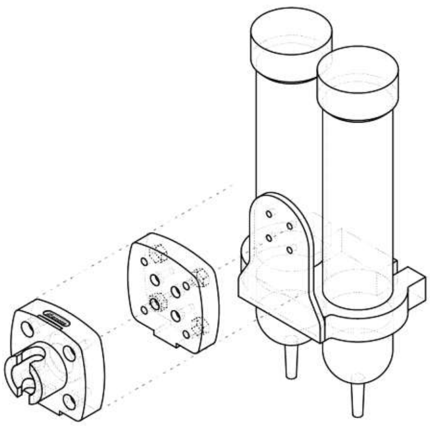

casted mixture 13. dry


casted mixture 13 + 7,7% wood flour. dry

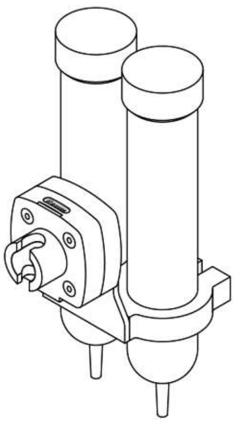
Robotic printing tests

To enable the realization of complex geometries, it is essential to use robotic fabrication methods. For this thesis, robotic 3D-printing tests were conducted, using the biomaterial that had been developed beforehand. The objective was to find the ideal printing parameters and eventually be able to print onto a curved 3D-surface.

The setup consisted of an industrial robot arm and a material extrusion tool, which included two cartridges with Luer-lock connectors compatible with a large variation of nozzles. The tool was mounted to the robot arm using a custom 3D-printed adapter. Air valves located on top of the cartridges were connected to a compressor via tubing, allowing extrusion to be controlled through air pressure that pushed the material through the nozzle. To maintain a consistent material temperature, a heating pad connected to a programmable power supply was wrapped around the filled cartridges.



tool flange of robot - 3D-printed adapter - extrusion tool

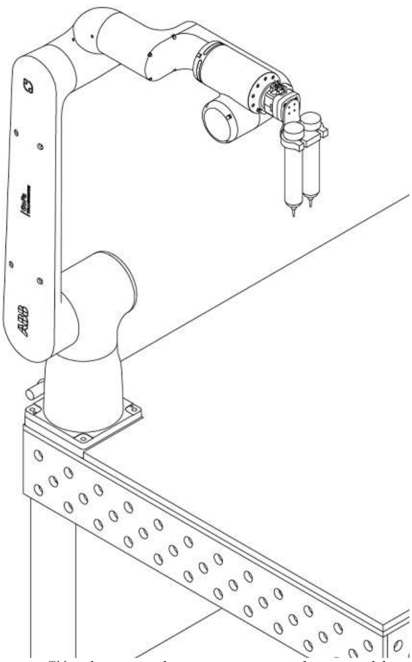


extrusion tool connected to tool flange

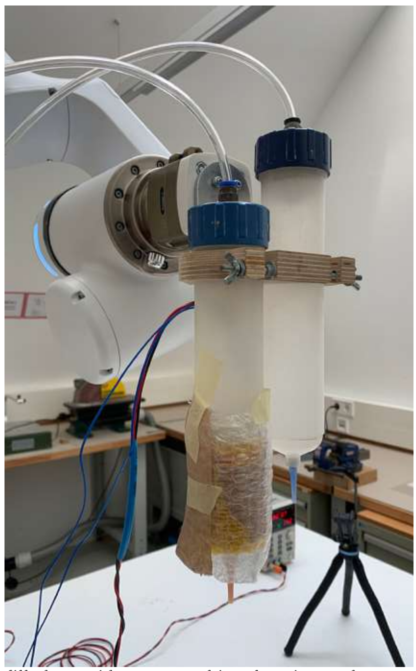
Printing on a 2D-surface

For testing, simple parametrically designed printing paths were created in *Grasshopper 3D*, allowing for quick adjustments between tests. Once the path was arranged, the biomaterial was prepared and filled into one cartridge. The tests were then printed onto plastic sheets. While the robot executed the movement and turned the air pressure on and off automatically, the intensity of the air pressure had to be regulated manually.

Printing speed, air pressure, material temperature, material properties, and height position of the nozzle all affect the print outcome. These parameters were initially tested by conducting print tests of a simple path on a 2D surface, trying to achieve a consistent printing line. All flat tests were conducted using the material mixture 13, first with a 2mm, then with a 1,5 mm nozzle.

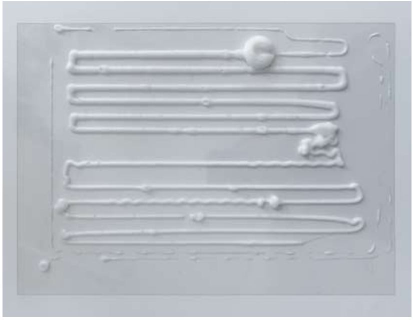


GoFa™ robot arm by ABB mounted on a table, with custom extrusion tool



filled cartridge wrapped in a heating pad

Results of printing on a 2D-surface



Test 1.2

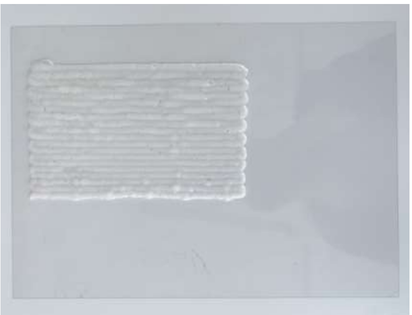
Operated manually

Material temp.	~55 °C
Nozzle size	2 mm
Nozzle height	~2 mm
Best result:	
Pressure approx.	0,25 bar
Speed approx.	~23 mm/s

Test 1.3

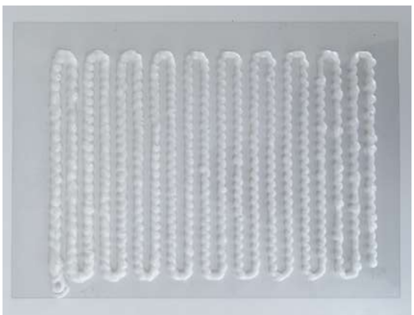
Operated manually

Material temp.	~55 °C
Nozzle size	2 mm
Nozzle height	~2 mm



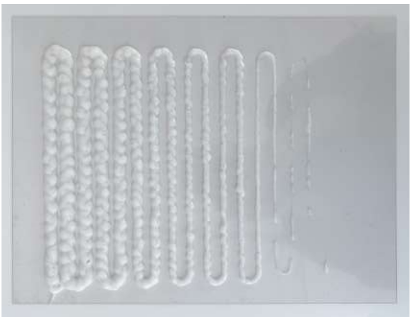
Test 2.1

Curve division	3 mm
Offset of lines	6 mm
Material temp.	~55 °C
Nozzle size	2 mm
Nozzle height	~3 mm
Pressure	0,25 bar
Speed	15-32 mm/s



Test 2.3

Curve division	3 mm
Offset of lines	15 mm
Material temp.	~40 °C
Nozzle size	2 mm
Nozzle height	4 mm
Pressure	0,25 bar
Speed	15-32 mm/s

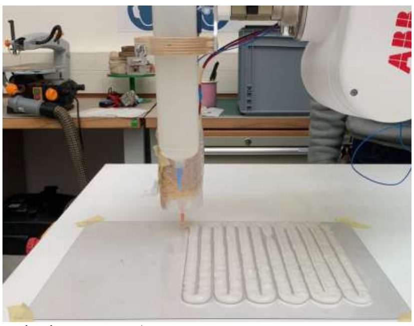


Test 2.4

Curve division	3 mm
Offset of lines	15 mm
Material temp.	~36°C
Nozzle size	2 mm
Nozzle height	3 mm
Pressure	0,25 bar
Speed	15-32 mm/s

Test 2.5

Curve division	3 mm
Offset of lines	15 mm
Material temp.	~39°C
Nozzle size	2 mm
Nozzle height	2mm
Pressure	0,25 bar
Speed	15-32 mm/s



printing test 2.5

For the initial two tests, the robot was controlled manually to gain a better understanding of the optimal speed, nozzle height, and material temperature. In further tests, the process was automated for which the printing speed was programmed to start at 15 mm/s and increase with each line, reaching 32 mm/s by the end. This helped identify the speed range that yielded the best printing results. Finally, for the last 2D tests, printing in layers was explored. The layers were perpendicular to each other to enhance structural strength.

Test 3.1, 2 layers

Curve division	3 mm
Material temp.	~40 °C
Nozzle size	1,5 mm
Nozzle height	2 mm
2nd layer	+ 5 mm
Pressure	0,25 bar
Speed	25 mm/s

Test 3.2, 2 layers

Curve division	3 mm
Material temp.	~40 °C
Nozzle size	1,5 mm
Nozzle height	2 mm
2nd layer	+ 5 mm
Pressure	0,25 bar
Speed	25 mm/s

Test 3.3, 2 layers

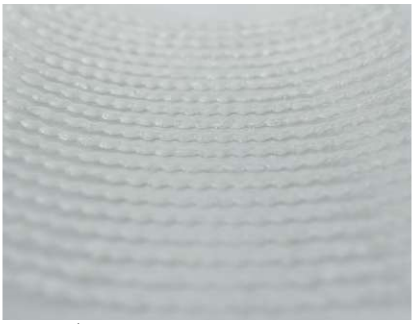
Curve division	3 mm
Material temp.	~40 °C
Nozzle size	1,5 mm
Nozzle height	2 mm
2nd layer	+ 4 mm
Pressure	0,25 bar
Speed	25 mm/s

Test 3.4, 3 layers

Curve division	3 mm
Material temp.	~40 °C
Nozzle size	1,5 mm
Nozzle height	2 mm
2nd + 3rd layer	each + 3mm
Pressure	0,25 bar
Speed	25 mm/s


test 3.1 dry


test 3.2 dry


test 2.3 dry

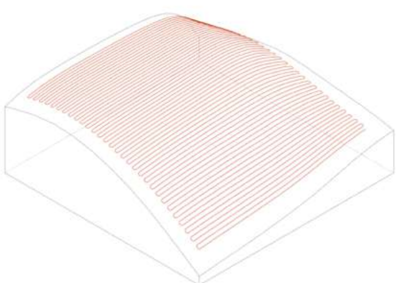

test 2.5 dry


test 2.5 dry

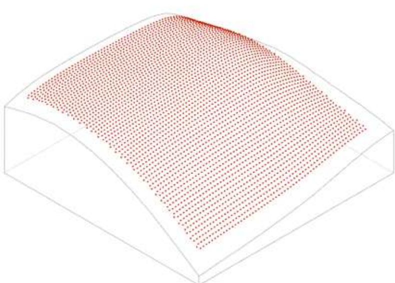
Printing on a curved 3D-surface

Once suitable printing parameters were established, 3D-printing on the curved prototype mould was tested. To do so, the printing path first had to be prepared. Before sending a printing path to a robot arm, it must be divided into discrete points, and a frame must be assigned to each point. The distance between the division points is another critical parameter that had to be tested beforehand, as it affects whether the robot can process the data and move smoothly at the given printing speed. Each frame includes the position of a point and its orientation in space, defined by three orthogonal vectors representing the X, Y, and Z axes. The robot moves and orients the tool along these frames, so they must be correctly oriented.

For the printing tests on a 2D-surface, the frames were all oriented in the same way since the tool only had to be moved orthogonal to the table and not rotated. For printing on a curved surface, however, the orientation had to be adapted. The frames were aligned to the curvature of the surface so that the printing tool remained perpendicular to it at each point along the path. Additionally, the digital surface of the mould had to be aligned with the position of the physical mould. This was done by manually moving the tool center point - which is the tip of the nozzle - to each corner of the mould. The frame of the current position of the tool center point could then be saved. After capturing all four corner points, they were used to align the digital surface to the actual position of the physical mould.

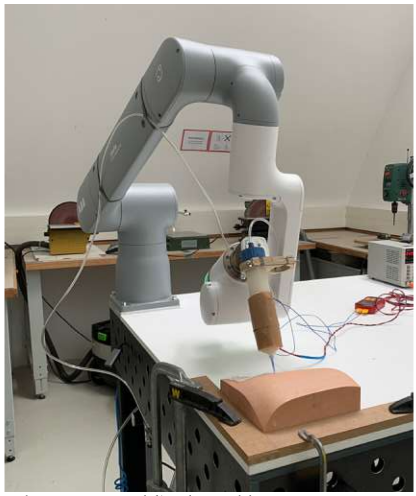


1. printing path

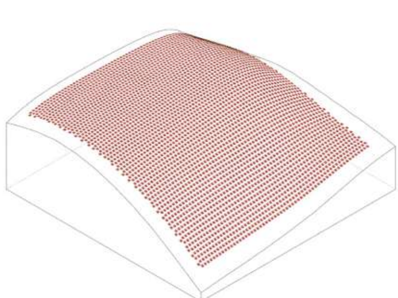


2. path divided into points

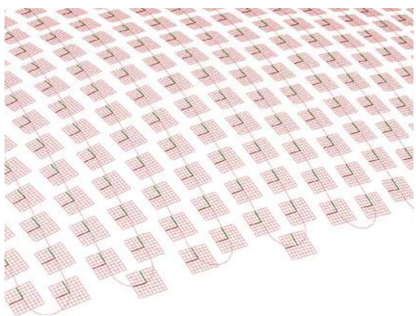
The remaining printing process was identical for both the curved and flat surfaces.
Before running the print, the robot's movement was tested without any material to ensure the correct printing height and to check for potential collisions with the mould. The nozzle height was then digitally adjusted to approximately 3mm above the surface. Since the mould had been used in previous manual printing tests and sanded in between, it differed slightly from the digital surface. As a result, the final printing lines were not completely consistent due to minor variations in nozzle height throughout the process. For the first test, the offset between the lines was set to 7mm, based on the expectation that the printed lines would be approximately 3–4mm wide. However, the pressure was slightly lower than in the initial tests, resulting in line widths of 2-3mm. Consequently, the offset was reduced to 3 mm for subsequent tests. In total, four curved printing tests were conducted on the prototype mould.



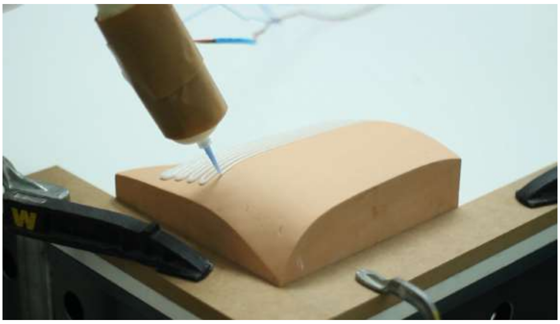
robot set-up and fixed mould

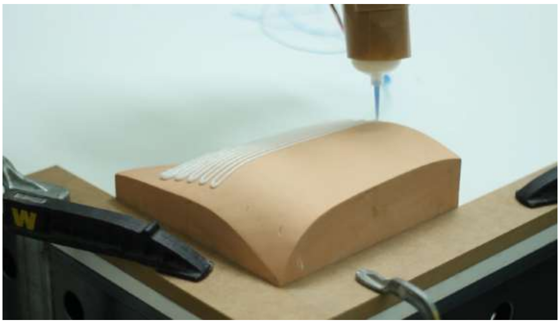


3. assigned and aligned frames

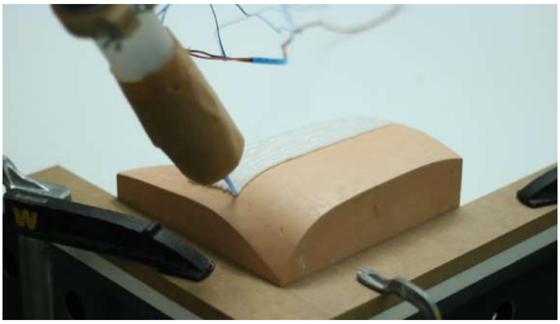


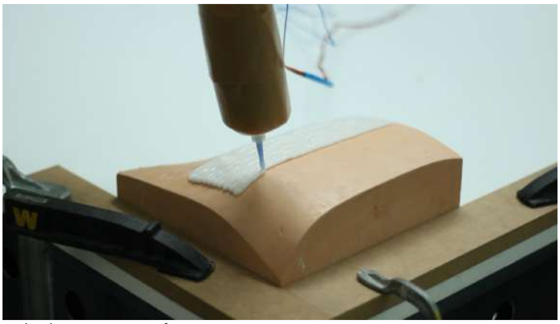
close up of frames perpendicular to surface





printing on 3D surface. test 1





printing on 3D surface. test 3

Final parameters used for printing on a curved 3D-surface

Curve division	3 mm	*Nozzle height*	~3 mm
Offset of lines	3 mm	*Pressure*	< 0,25 bar
Material temp.	~40 °C	*Speed*	25 mm/s
Nozzle size	1,5 mm		

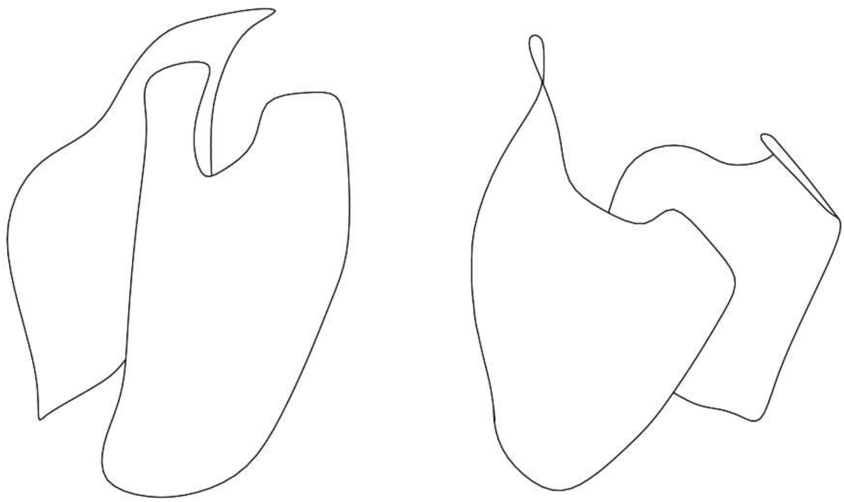
printing on 3D surface. test 4. result

Fabricating

Moulds

To realize the wearable with the tested materials, the approach was to cast all layers on the same moulds individually and later connect them with each other.

The moulds were created by digitally aligning the front and back base shape of the design in a vertical orientation and extruding them to form 3D objects. A rectangular base was added to each mould to facilitate alignment on the robot table for printing. The objects were then milled from Ureol and sanded to achieve a smooth surface. Finally, a release agent was applied to enable easy removal of the cast objects.



design base shapes

mould. front

mould. back

Latex elements

Inflatable

The design includes two individual inflatable elements. Each inflatable consists of two thin latex layers welded at their edges. The side intended to inflate is thinner than the side that should remain its shape. To create these sheets, latex was applied to the moulds in thin layers using a very soft brush. Each layer was allowed to dry for 20 minutes before the next was applied. The thin sheets meant to inflate consist of only two layers, while the other non-inflating sides consist of five.

After drying for 24 hours, the latex sheets were coated with talcum powder to prevent it from sticking to itself. This powder also contributes to the soft feel of the latex. Finally, the sheet could be slowly removed from the mould.

creating latex layer


latex element. thick. front


latex element. thick. front.

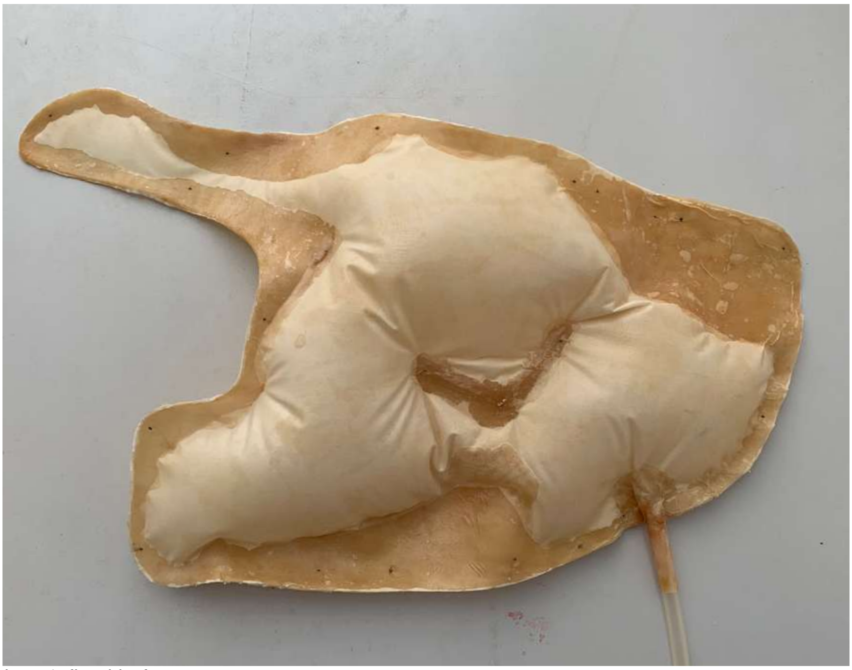
Connecting latex sheets and integrating air pumps

To complete the inflatables, the latex sheets were welded together at their edges. A template showing the design's holes was first drawn onto the mould to indicate which areas should remain inflatable and which should be connected. In the connecting areas, additional liquid latex was applied before placing a second latex layer on top to bond them. During this step, the silicone tube used to pump in air was also integrated. By applying latex to the first few centimetres of the tube, a simple valve was formed.

connecting latex layers

connecting latex layers

creating latex valve

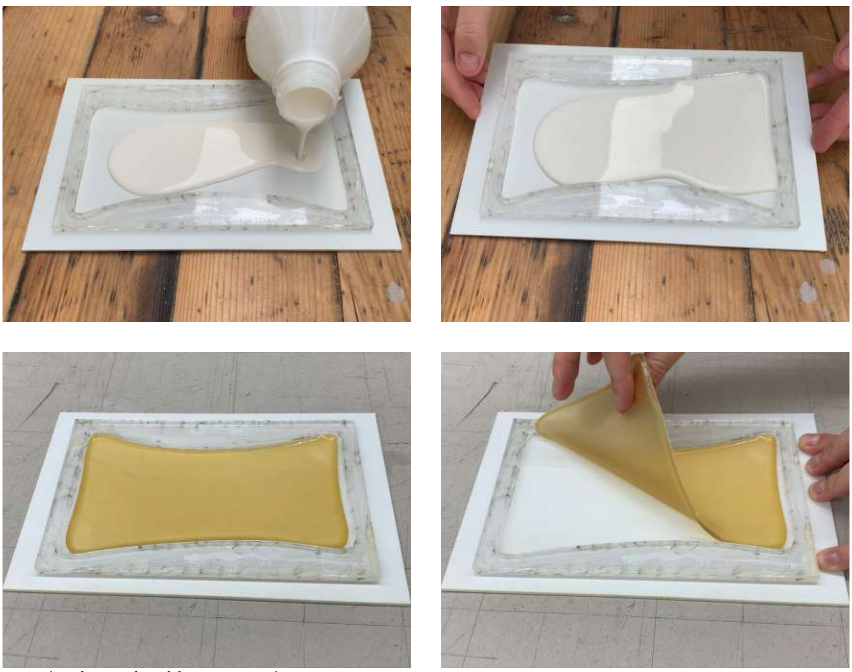

latex inflatable. front


latex inflatable. back

Shoulder connection

The element connecting the front and back parts over the shoulder is also made from latex. To ensure strength, this part was designed as a thick sheet and cast to achieve a smooth, even surface.

To create the mould, the digital design was first unrolled using *Grasshopper 3D*. The shape was then cut from acrylic glass sheets using a laser cutter. These pieces were glued together to form the mould and then latex was simply poured into the mould and evenly distributed by tilting. After one day of drying, the element could be removed and coated with talcum powder. Finally, the holes through which this part would be connected to the other elements were punched.



creating latex shoulder connection

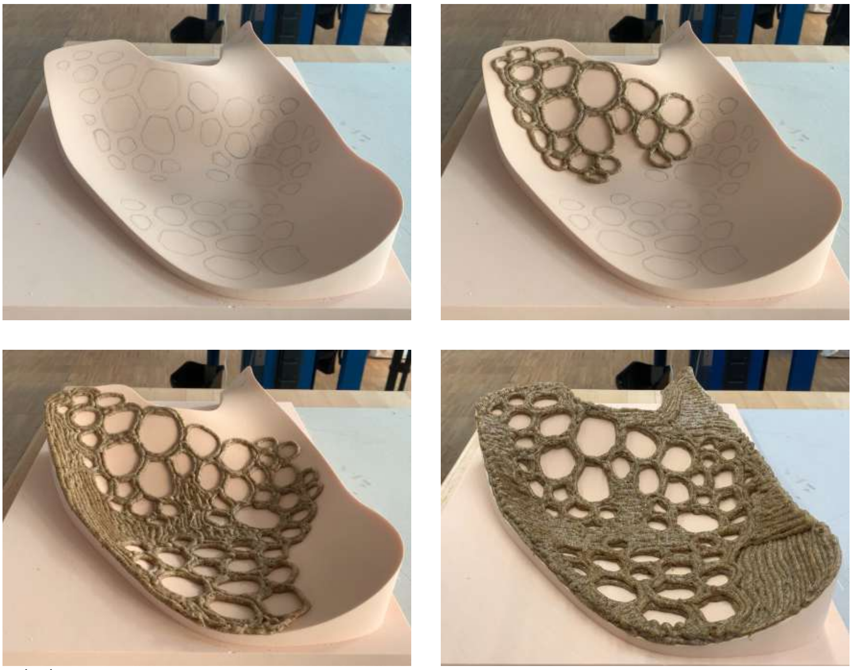
These photos clearly show how latex changes its colour over time. This is due to oxidation, which begins when natural latex is exposed to UV light and air.

latex shoulder connection with punched holes

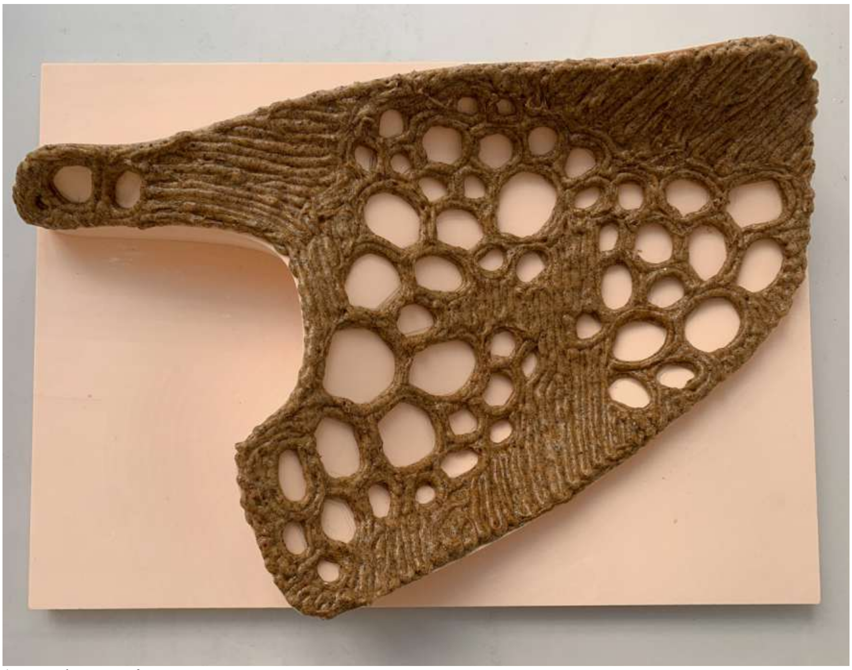
Manually printed elements

Printing inner elements

Since the robotic printing tests had not yet been completed, it was decided to print the elements manually. To enable the manual printing process, the designs first had to be transferred onto the moulds. This was done by laser cutting the flattened design from cardboard and using the cutout as a guide to draw it onto the moulds. Mixture 13 with 7,7% additive was used for the final inner elements. Using a syringe with a 4 mm nozzle, the drawn-on path of the holes was printed first, followed by filling in the remaining areas. For the second layer, this order was repeated, but this time perpendicular to the first layer. Throughout the printing process, the material was kept warm in the pot continuously, but had to be processed quickly to not cool down in the syringe. As the printing process was meant to be robotically done but simulated manually, the results are only an approximate replication of the digital design.



printing process



inner element. front

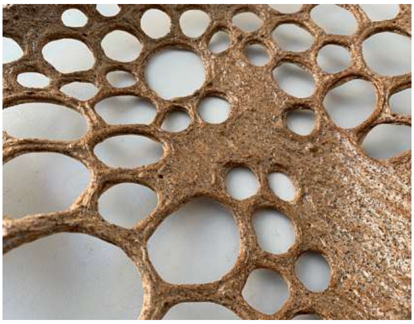
inner element. back

Further processing inner elements

After one week, the elements were fully dried. Using a small scraper, they were carefully removed from the moulds. Although a release agent had been applied before printing, the material adhered to the Ureol, making removal rather difficult. However, after some effort, the pieces were successfully detached.
A Dremel was used to sand both the inner edges of all holes and the outer contours. Smooth edges were essential to prevent damage to the inflatable elements later on.

detaching

sanding



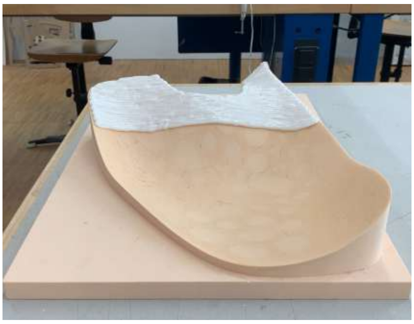
close-ups

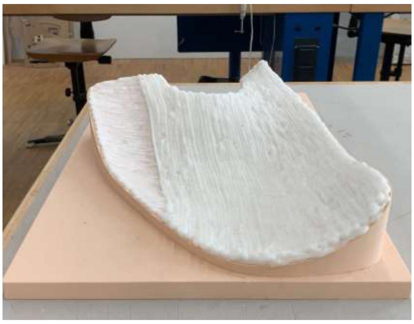

inner element dry and sanded. front


inner element dry and sanded. back

Printing shells I

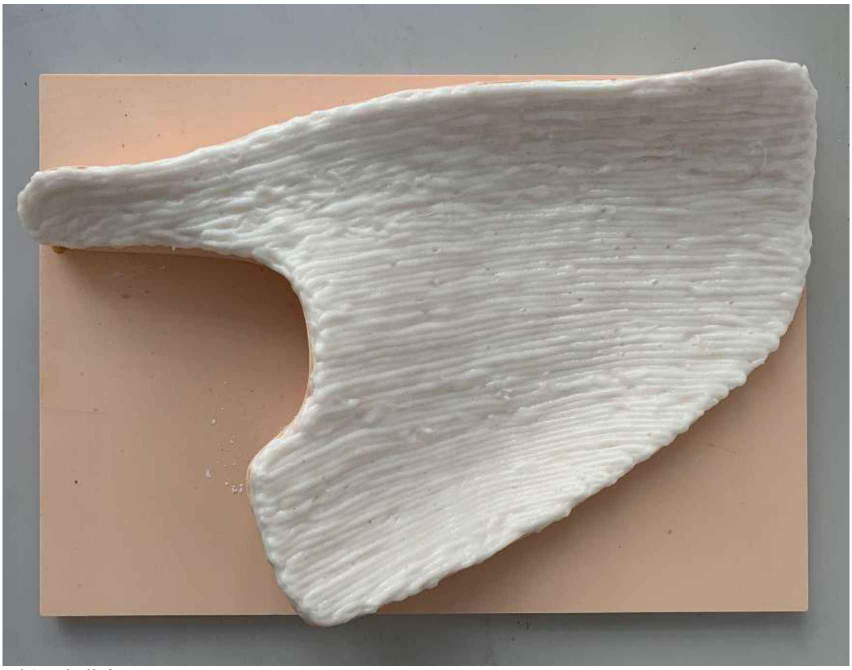
The process for printing the outer elements was the same as for the inner elements; however, no additive was used this time as this element did not need to be as rigid as the inner element. An effort was made to print the first layers in one continuous direction, with the second layer applied perpendicularly. After printing the results looked nice and even. However, unfortunately these elements started to mold a bit while drying and therefore were not used for the wearable.





printing process

mould appeared during drying time

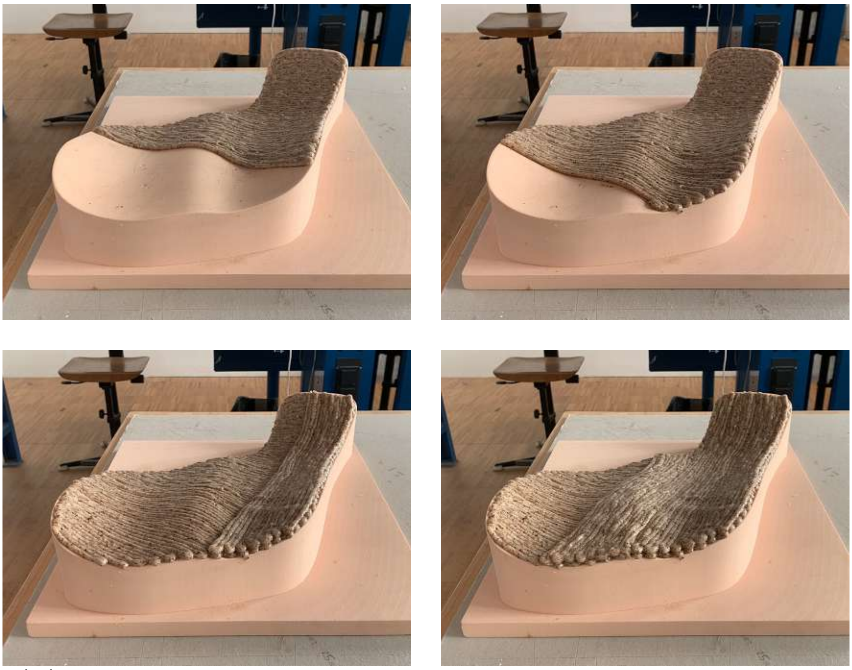


white shell. front

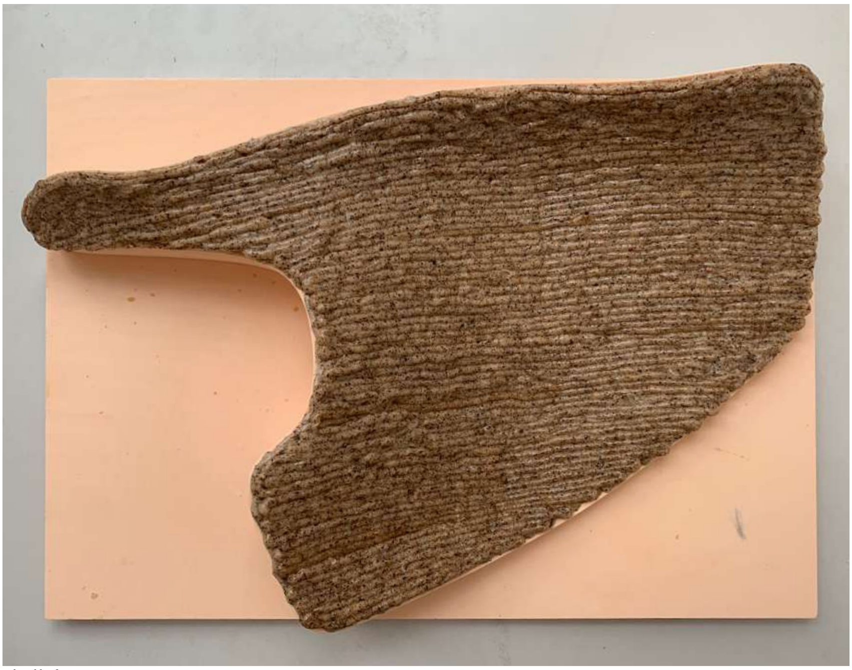
white shell. back

Printing shells II

For the new shells Mixture 13 with 3,33% wood flour additive was used. Again, the two layers were printed perpendicular to each other to improve strength. The printing process went smoothly, and the result appeared to be even and consistent.



printing process



shell. front

shell. back

Further processing shells

After one week of drying, the shells were detaching from the moulds, then sanded to achieve smooth edges. The visible side of these elements is now what was the bottom side of the print. This side shows different tactile and visual properties, as it is not as even as the upper side and the printing lines are much more recognizable.

To complete preparations for assembly, the holes for the book screws had to be drilled. First, their positions were marked on the digital models and then transferred to the physical models. During drilling, the inner elements were clamped to the shells to ensure consistent positioning. The holes were then also transferred onto the inflatables and cut out.


surface close-ups

front. outer element dry

back. outer element dry

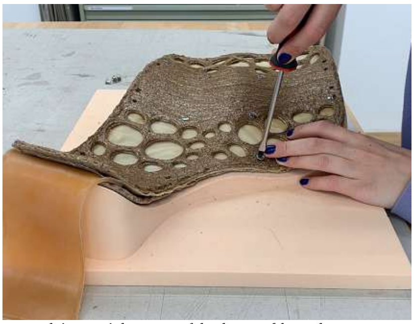
outer element. front

outer element. back

Assembly

The assembly had to be carried out in a specific order. First, the first halves of the book screws were inserted into the holes of the shells and placed onto the moulds for stability. Next, the holes of the inflatable were put over each according book screw. During this step the latex shoulder element had to be integrated as well. Then, the inner elements were put on top and attached with the second halves of the book screws. As the layers were all connected, the silicone tubes forming the closure elements were inserted through the according holes at the side and closed with cord stoppers. Finally the air pump was included, also via silicone tubes which were additionally secured to the inflatable with some more liquid latex.


adding inflatable onto shell


attaching with second halves of brook screws


attaching air pump to inflatable


adding silicone tubes

shoulder connection detail

silicone tubes and cord stoppers form closures

43

44

prototype

45

46

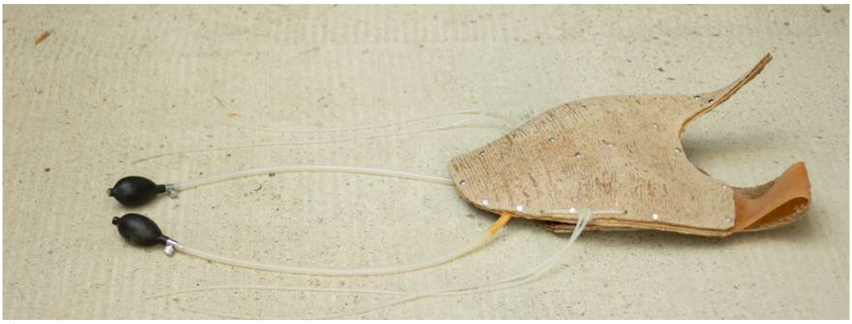
47


48 deflated


49 inflate

prototype

50


51


52


53

prototype

Conclusion

This thesis is an attempt to heighten the awareness of the tactile sense through an inflatable wearable, using the design process as a medium to experiment with biomaterials and advanced design and fabrication methods. Tactile, visual, and structural inspiration were drawn from soap bubbles and translated into an inflatable object and a skeleton which defines the areas and size of inflation. This idea was used to design a wearable whose purpose is to simulate the pleasant experience of a hug, and therefore direct attention to what is perceived with the skin.

The design was created using a variation of analogue and digital design tools, computationally processing a physically captured hug map into a holey structure. This structure is the inflation defining element, enabling the hug simulation. The size of holes and struts are adjustable in the *Grasshopper 3D* script according to desired result. The wearable is designed for the upper body and intended to fit various body types.

With the intention of using bio-based materials for fabricating the design, natural latex was used to make the inflatable parts. For the rigid elements, a strong biomaterial was developed. The aim was to create a material with the right properties to be 3D-printable. Through several tests, a suitable mixture consisting of gelatine, xanthan gum, glycerine, water, and a bio-additive – wood flour – was found. Using an industrial robot arm, the 3D-printing process was then tested in a couple of trials but not yet used to create the final parts. For the wearable, the biomaterial elements were manually printed on a 3D-milled mould. The latex inflatables were also manufactured manually using these moulds.

People's feedback

To test the wearable's effect, various people tried the design and were asked about their experience. When people wear the design for the first time, it is noticeable that they seemingly get more introverted for the duration of the experience. Fully concentrating on the stimulation and putting their attention to what they perceive with their body. While actively inflating, most stopped talking and gazed into the distance, seemingly shifting their attention away from their visual sense for a moment.

One person stated that the pressure is perceptible, and the wearable feels like an "airbag". Another noted a pleasant feeling from the pressure, as well as a supporting effect on body posture. She enjoyed the feeling of how it made her stand up straight, as the wearable acts like an exoskeleton, especially in the back, yet not feeling like an armour due to its light weight.
This feedback suggests that the wearable increases awareness of both body posture and touch – key components of the tactile sense. When asked whether they felt restricted in their movement or had an urge to move, participants noticed that the wearable subconsciously encouraged them to stand still without feeling restricted.

Overall, the wearable evokes a sense of protection as it makes one stand up straight and keep a confident and strong posture. It fits to various body types, but it is not ideal for everybody. Especially the front of the upper body various a lot from person to person which makes a universal design challenging. Even though the inflation pressure is weaker than intended, the experience of wearing the design and engaging with it, draws the attention to the tactile sense.

Limitations

As mentioned before, achieving a universally fitting design was difficult, especially since the wearable is rigid and non-flexible. Although many design decisions were made to accommodate a wide range of users, the high variation in human body types makes it nearly impossible to achieve a good fit for everyone.

The developed biomaterial exhibits good properties for 3D-printing and shows rigid and strong characteristics when dry. While it can withstand a certain level of force of inflation, it eventually breaks under excessive stress.

Although the initial goal was to fabricate parts of the design by robotically 3D-printing the biomaterial onto curved moulds, this thesis ultimately includes only a number of printing trials, during which suitable print settings such as speed, air pressure, and material temperature were tested.

Further steps

To eventually be able to robotically 3D print the design, further printing tests need to be conducted. The aim is to find ideal settings for the printing path information, which is given to the robot, as well as printing speed, extrusion pressure, and material temperature. Furthermore, it is recommended to add an air pressure regulator for the extruder to improve the printing quality.

It is also suggested to try further variations of the material mixture to improve its overall properties. One possibility might be to reduce the water percentage to make it less liquid and, ideally, minimize shrinkage even further.

Bibliography

Sources

'3D Printing Bioplastics – Materiability'. Accessed 10 March 2025. https://materiability.com/portfolio/3d-printing-bioplastics/.

Aguahoja. 'Aguahoja'. Accessed 13 May 2025. https://oxman.com/projects/aguahoja.

Art Basel. *'How Rebecca Horn expanded the boundaries of the human body'*. Accessed 6 March 2025. https://www.artbasel.com/news/rebecca-horn-museum-tinguely-koerperfantasien-art-basel.

Babydeepsleep. *'BABYDEEPSLEEP® - Besserer Schlaf für die ganze Familie'*. Accessed 24 May 2025. https://babydeepsleep.com/de-at.

Bart Hess. *'Bart Hess | LucyandBart'*. Accessed 12 May 2025. https://www.barthess.com/lucyandbart.

'Behnaz Farahi'. Accessed 12 May 2025. https://behnazfarahi.com/bio/.

BIG | Bjarke Ingels Group. *'Skum Pavilion'*. Accessed 24 March 2025. https://big.dk/ projects/skum-pavilion-12388.

'Body Architecture 3.0 – Studio Filippo Nassetti|PAACADEMY'. Accessed 12 May 2025. https://paacademy.com/course/body-architecture-3-0-studio-filippo-nassetti.

Dunne, Margaret. *Bioplastic Cook Book.* Barcelona: FABTEXTILES Iaac, 2018.

Foksal. *'Comfort #8'*. Galeria Foksal, 10 September 2010. https://www.galeriafoksal.pl/en/comfort-8/.

Forsell, Lena M., and Jan A. Åström. *'Meanings of Hugging: From Greeting Behavior to Touching Implications'*. Comprehensive Psychology 1 (January 2012): 02.17.21.CP.1.13. https://doi.org/10.2466/02.17.21.CP.1.13.

Grandin, Temple. *'Calming Effects of Deep Touch Pressure in Patients with Autistic Disorder, College Students, and Animals'*. Journal of Child and Adolescent Psychopharmacology 2, no. 1 (January 1992): 63–72. https://doi.org/10.1089/cap.1992.2.63.

'Hans Hemmert's Yellow Blobs & Life-Sized Balloon Tank'. Accessed 24 March 2025. https://publicdelivery.org/hans-hemmert-german-panther/.

Haynes, Alice C., Annie Lywood, Emily M. Crowe, Jessica L. Fielding, Jonathan M. Rossiter, and Christopher Kent. *'A Calming Hug: Design and Validation of a Tactile Aid to Ease Anxiety'*. Edited by Desmond J. Oathes. PLOS ONE 17, no. 3 (9 March 2022): e0259838. https://doi.org/10.1371/journal.pone.0259838.

Iris van Herpen. *'Iris van Herpen, Exhibition, Sculpting the Senses'*. Accessed 12 May 2025. https://www.irisvanherpen.com:443/sculpting-the-senses.

Iris van Herpen. *'Sensory Seas | Haute Couture'*. Accessed 12 May 2025. https://www.irisvanherpen.com:443/collections/sensory-seas.

Jones, Lynette. *Haptics.* The MIT Press Essential Knowledge Series. Cambridge, Massachusetts London, England: The MIT Press, 2018.

Kaidaniuk, D.O., M.M. Tertychniy, and A.V. Drazhnikova. *'Xanthan Gum as a Component of Starch-Based Bioplastic'*. Problems of Environmental Biotechnology, no. 1 (1 February 2023). https://doi.org/10.18372/2306-6407.1.17141.

Kartika, Larasati. *'Wearable Architecture'*. Medium (blog), 3 August 2021. https://medium.com/@laraskartika99/wearable-architecture-15a244df997e.

Koemer, Julia. *'Digitally Crafted Couture'*, 3D-Printed Body Architecture, 87, no. 06 (October 2017): 40–47.

'Latex'. Accessed 7 March 2025. https://en.wikipedia.org/wiki/Latex.

Leach, Neil. *'What Is 3D-Printed Body Architecture'*, 3D-Printed Body Architecture, 87, no. 06 (October 2017): 6–15.

Lucy McRae. *'Lucy McRae – World Renowned Sci Fi Artist and Body Architect'*. Accessed 12 May 2025. https://www.lucymcrae.net.

'Natural Rubber'. Accessed 7 March 2025. https://en.wikipedia.org/wiki/Natural_rubber.

Neff, Dr. Megan Anna. *'Weighted Vests, Autism, & Why and How to Use Them - Neurodivergent Insights*'. Accessed 7 March 2025. https://neurodivergentinsights.com/blog/weighted-vests-autism/.

Nicholas, Paul, Ayoub Lharchi, Martin Tamke, Carl Eppinger, Konrad Sonne, Gabriella Rossi, and Mette Thomsen. *Biopolymer Composites in Circular Design: Malleable Materials for an Instable Architecture,* 2023.

OTO the hugging chair. *'OTO Le Fauteuil à Étreindre Archives'*. Accessed 23 April 2025. https://www.oto-chair.com/category/oto/.

Oxford Languages. *'Comfort'*. In Oxford Languages Online Dictionary. Oxford University Press. Accessed 12 March 2025. www.oxfordlanguages.com.

Oxman, Neri. *'Dermi Domus - A Grown Wardrobe for Bodies and Building'*, 3D-Printed Body Architecture, 87, no. 06 (October 2017): 16–25.

Palcova, Claudia. *Printing with Biofoams: Transient Futures Exploration.* Edited by Manuel Kretzer. Cambridge, Ontario: Riverside Architectural Press, 2022.

Pallasmaa, Juhani. *The Eyes of the Skin: Architecture and the Senses.* Fourth edition Hoboken, NJ: Wiley, 2024. https://doi.org/10.1002/9781394200702.

Ribul, Miriam. *Recipes for Material Activism*, 2014.

Rodríguez, Cesar. *'Biomaterials 101: From Organic Waste to Material Gold – Fab Lab Barcelona | Research, Education, Innovation Centre'*. Accessed 10 March 2025. https://fablabbcn.org/blog/emergent-ideas/biomaterials-101.

Schönhammer, Rainer. *Einführung in die Wahrnehmungspsychologie: Sinne, Körper, Bewegung.* 2., Überarb., Aktualisierte u. erw. Aufl. UTB 3142. Wien: Facultas.wuv, 2013.

Science World. *'Bubble Sculptures'*. Accessed 12 March 2025. https://www.scienceworld.ca/resource/bubble-sculptures/.

Sherazi, Syeda Abida Hussain, Wajid Awan, Maira Kazmi, Kanwal Mahmood, and Anees Mahmood Awan. *'Perils of Tight Clothing; A Survey Report'*. International Islamic Medical Journal 3, no. 1 (17 February 2022): 6–15. https://doi.org/10.33086/iimj.v3i1.1913.

SiiGii | Official Site. *'SiiGii | Official Site'*. Accessed 24 March 2025. https://www.siigii.com.

Taubin, G. *'Dual Mesh Resampling'*. In Proceedings Ninth Pacific Conference on Computer Graphics and Applications. Pacific Graphics 2001, 180–88. Tokyo, Japan: IEEE Comput. Soc, 2001. https://doi.org/10.1109/PCCGA.2001.962871.

'TBK'. Accessed 22 May 2025. https://tbk-research.webflow.io/.

TherapieWelt.de. *'Die Vorteile von Kuscheltieren mit Gewicht'*. Accessed 24 May 2025. https://therapiewelt.de/blogs/news/die-vorteile-von-kuscheltieren-mit-gewicht.

TherapieWelt.de. *'TherapieWelt.de - Produkte für besseren Schlaf, gegen Stress und Angst'*. Accessed 24 May 2025. https://therapiewelt.de/.

Water-Based Fabrication. *'Water-Based Fabrication'*. Accessed 13 May 2025. https://oxman.com/projects/water-based-fabrication.

'What Is Tactile Sensitivity? | Connect n Care ABA'. Accessed 7 March 2025. https://www.connectncareaba.com/blog/tactile-sensitivity.

Images

1–8 Nordmann, Nikolai; Keiblinger, Laura. *Soap Bubbles.* 2024.

9 Horn, Rebecca. *Scratching Both Walls at Once.* 1974-1975. https://www.artbasel.com/news/rebecca-horn-museum-tinguely-koerperfantasien-art-basel?lang=de

10 *Squease*™. https://squease.nl/?lang=en

11 *Squease*™ *hidden in a jacket.* https://squease.nl/?lang=en

12 Grandin, Temple. *Squease machine.* 1992. https://4mdmedical.com/products/the-squeeze-machine/

13 Audrain, Alexia. *OTO the hugging chair.* 2019. https://www.oto-chair.com/

14 Therapiewelt.de. *Gewichtskragen für Kinder.* https://therapiewelt.de/collections/gewichtskragen/products/gewichtskragen-fur-kinder-kunterbunte-motive

15 Therapiewelt.de. *Gewichtsmantel – Für den Alltag und auf Reisen.* https://therapiewelt.de/collections/gewichtsprodukte/products/therapiemantel-fur-den-alltag-und-auf-reisen

16 Hemmert, Hans. *Yellow Sculpture Fitting to Mona Standing.* 1998. https://publicdelivery.org/hans-hemmert-german-panther/

17 SiiGii. *Floating above limits.* 2020. https://www.siigii.com/#/sun-allergy-diaries-day2/

18 L/B. *Comfort #8.* 2010. https://www.galeriafoksal.pl/en/comfort-8/

19 BIG. *Skum Pavilion.* 2016. https://big.dk/projects/skum-pavilion-12388

20 LucyandBart. *Untitled.* 2010. https://www.lucymcrae.net/lucyandbart

21 LucyandBart. *Germination day one.* 2010. https://www.lucymcrae.net/lucyandbart

22 Oxman, Neri and members of the Mediated Matter Group in collaboration with Stratasys and Iris van Herpen.. *Mushtari.* 2015. https://3dprintedart.stratasys.com/fashion/project-one-tg5ld-c24df-gzm69-wam56-r8zsy-xj5yw-zjdkj

23 Oxman, Neri and members of the Mediated Matter Group in collaboration with Stratasys. *Anthozoa.* 2013. https://3dprintedart.stratasys.com/fashion/anthozoa-skirt-and-cape

24 Farahi, Behnaz. *Caress of the Gaze.* 2015. https://behnazfarahi.com/caress-of-the-gaze/

25 Farahi, Behnaz. *Opale.* 2017. https://behnazfarahi.com/opale/

26 Van Herpen, Iris. *Sensory Seas.* Process Film. Screenshot.2020. https://youtu.be/f30Qj_fogXU?si=q22NQeadns62id80

27 Van Herpen, Iris. *Sensory Seas.* Look 12. 2020. https://www.irisvanherpen.com/collections/sensory-seas/editorial-2

28 Van Herpen, Iris. *Sensory Seas.* Look 19. 2020. https://www.irisvanherpen.com/collections/sensory-seas/editorial-2

29 Van Herpen, Iris. *Sensory Seas.* Look 15. 2020. https://www.irisvanherpen.com/collections/sensory-seas/editorial-2

30 Oxman, Neri. *Aguahoja.* 2019. https://oxman.com/projects/aguahoja

31 Oxman, Neri. *Water-based fabrication. Nozzle printing chitin pattern.* https://oxman.com/projects/water-based-fabrication

32 Oxman, Neri. *Water-based fabrication. Close-up of chitosan sample 13.* https://oxman.com/projects/water-based-fabrication

33 CITA. *Generated print path.* 2023. https://royaldanishacademy.com/en/case/radicant

34 CITA. *Biomaterial test with recycled cotton.* 2023. https://royaldanishacademy.com/en/case/radicant

35 CITA. *Print with seagrass and bark fibrous.* 2023. https://royaldanishacademy.com/en/case/radicant

36 CITA. *Radicant.* 2023. https://royaldanishacademy.com/en/case/radicant

37-42 Nordmann, Nikolai. *Hug map.* 2025.

43-53 Nordmann, Nikolai. *Comfort zone: an inflatable tactile wearable.* 2025.

All other images by Laura Keiblinger.