Smart Aging:

How Smart Materials in Architecture Can Respond to Changing User Needs

by
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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

As smart materials and digital fabrication technologies advance in architecture, environments can increasingly respond and interact with their users. One area of interest is the development of habitats that respond and adapt to the needs of seniors to create safer environments to age-in-place. With the baby boomer generation reaching retirement age, the problems seniors face in the built environment place a growing pressure on us to reconsider where they live. Few designers, however, apply contemporary technological advancements in architecture to innovate the practical and social environments of seniors. This thesis explores how smart materials can prolong aging-in-place by addressing common environmental problems seniors face in their homes.

Rather than considering aging as a barrier of design, this research places seniors as drivers of design inspiration and innovation for creating environments that care for their users. This thesis has three design experiments that follow three parts, each addressing a stage in the design process. The first investigates the relationship of seniors to the built environment through qualitative research and identifies three moments of vulnerability: falling, slipping, and thermo-regulation. The second identifies smart materials that would best respond to mitigating those vulnerabilities through a critical survey of multiple material properties for each moment. It also introduces preliminary design concepts for each intervention using those materials. The final part consists of an iterative cycle between prototyping and designing, resulting in a proof of concept design and prototype for each intervention: lightweight and form fitting protective apparel to protect against falling; a water responsive floor system that enhances grip and indicates wetness to prevent slipping; and a heat and humidity responsive screen system that allows environments to thermally self regulate. Each design experiment grows out of a continuous negotiation between digital fabrication, material behavior, and user needs, reciprocally enriching each other throughout the process.

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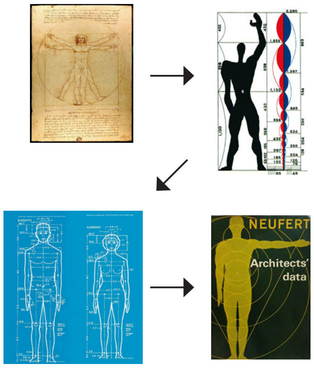
Introduction

Our bodies are constantly responding to changing conditions of our environments. When it's dark, our eyes dilate to bring in light, in water our fingers develop grip, and when it is hot, we release sweat to cool down. Our bodies are equipped with these responses to help us inhabit diverse conditions of our environment. With age, however, our abilities naturally deteriorate, exponentially changing how we interact with and experience space.[1] New obstacles and moments of challenge therefore emerge in varying degrees, from difficulty navigating in the dark[2] to an inability of using stairs[3]. While each incident alone might seem minor, together they progressively disable us from inhabiting even our own homes. As our bodies deviate from our initial abilities, the built environment becomes gradually more inaccessible to us, disrupting our accustomed ways of life. Within this regression we typically put our efforts to improving ourselves and how we might stall our bodies from aging. As a result, we have seen significant advancements in human prosthetics and small-scale industrial interventions for seniors (Fig.1). Architecture, however, has remained slow in this advancement. Even architectural guidelines such as *Neufert's Architecture's Data* did not include accessible design considerations until 2012 and is still very limited in specifics about aging users.[4] The repercussions of our inaction and shortcomings in addressing problems seniors face in architecture are now beginning to surface. For instance, as the world experiences a large demographic shift where seniors (60+) are projected to account for 20% of the global population by 2030, the place of aging in architecture becomes more apparent.[5] Despite the desire by the majority of baby boomers in Canada to age in place for the future, environmental factors still remain one of the leading contributions to aging in place failure, pressing architects to meet those demands.[6] This thesis argues that the heart of the problem is not in our occupants nor aging; but in how we design architecture.

Fig.1 Contemporary industrial design for seniors and disability
Top: Scooter for Life by Priestman Goode [Adam Woodward]
Bottom: Superstar, Modern Light-weight Wheel chair by Kuschall

How architecture disables



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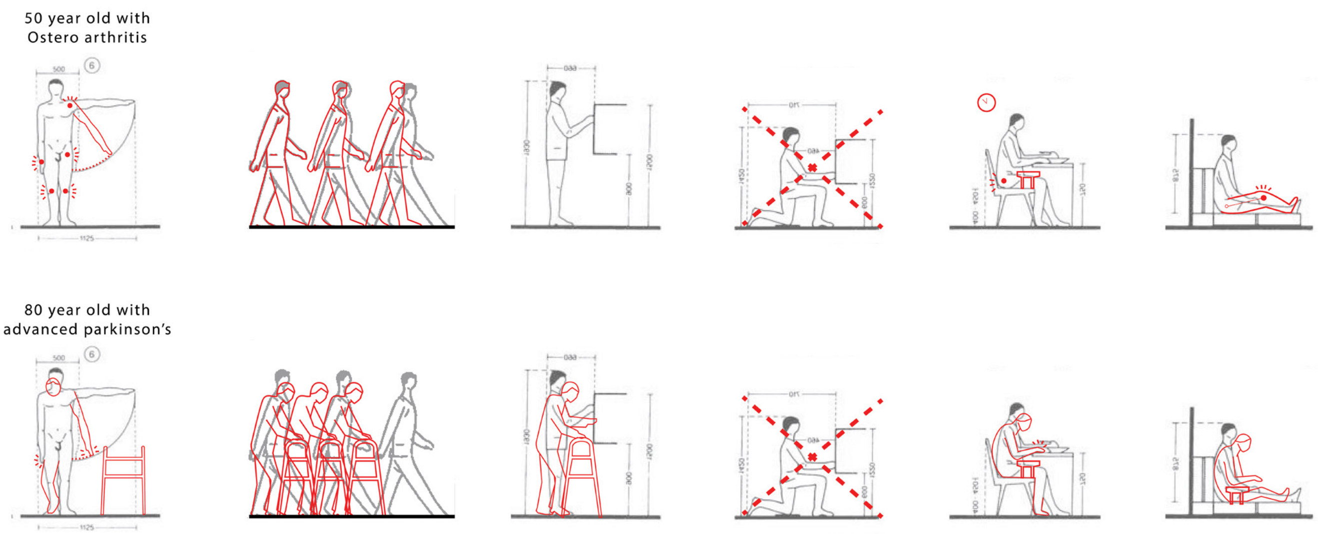
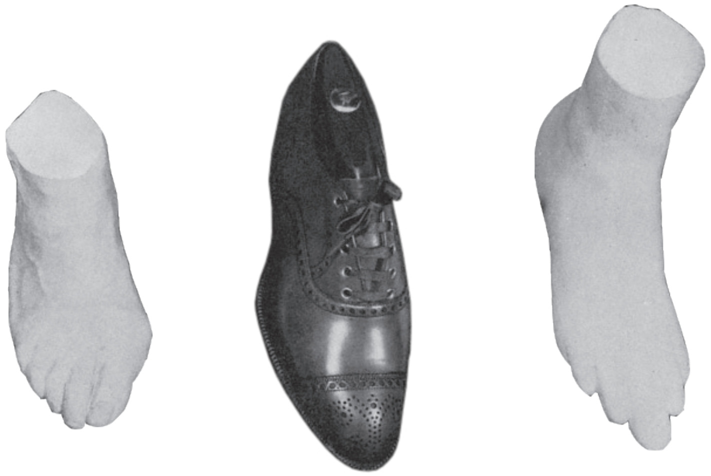
Since the advent of the Vitruvian Man, architecture has continuously evolved the idea of designing around the 'average' occupant, creating standardizations such as Corbusier's Modular, Joe and Joesphine, and ultimately the Neufert's Architecture's Data, to help architects design in relation to human scale (Fig.2).These standards use a method of 'one-size-fits-all', where it sets out a single human scale figure to represent the spectrum of occupants in our buildings. Often times, however, we all experience discrepancies between our bodies and the environment. Whether it is a shelf that is too tall to reach, or a door handle we can't open, these moments indicate a disproportion between us, and the standards used to design our environments[7]. These moments are what Kat Holmes, inclusive design theory author, calls 'misfits', where the environment does not match to the user's abilities, resulting in an inability of use[8]. Due to the large spectrum of users that occupy our built environments, everyone experiences these misfits in their daily lives. For those who fall closer to the 'average' of architectural standards, the misfits may be a few mere inconveniences that are tolerable and non-disruptive to their daily lives. For those who diverge further from the 'average', such as people with physical impairments or seniors, these misfits are often detrimental, disabling them of their daily activities. Some people with disabilities have even said that these misfits in the built environment are more disabling then their actual physical impairments themselves.[9]In the 1970's, disability activists in the Union of the Physically Impaired Against Segregation (UPIAS) in the UK, adopted a second definition for disability called the 'social model of disability'.[10] It defines the main factors of disability as societal, where those who designed the built environment lacked consideration for the occupants' physical impairments and are therefore, responsible for causing the physical and social barriers that the people with disability experience. [11] This definition widely differed from the common definition or attitude used in architecture at the time called the 'medical model' of disability.[12] The 'medical model' viewed disability as an individual problem, requiring disabled individuals to change, adapt and fit into the environments provided by architects .[13] The social model of disability, therefore, provided a new perspective of architecture and "called for environments to be designed in a way that anticipates the needs of people with disabilities and for their entitlements to gain equal access [...] playing a major and important role in new polices to eliminate social and architectural barriers" .[14] While we have certainly seen improvements in architecture to provide equal access to all occupants since these policies were put in place, these requirements still only represent the minimum to providing equal access and experience. The attitudes of in the medical model's view on disability is still heavily prevalent in architecture, continuing the systemic marginalization of disabled people in our built environments today.





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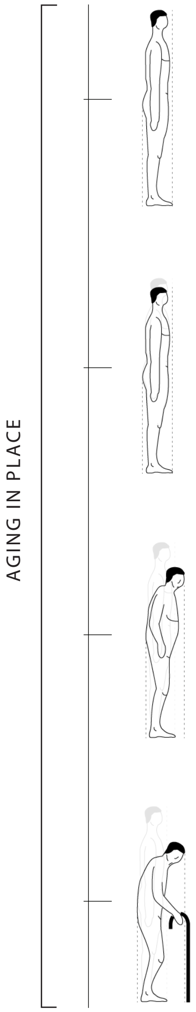


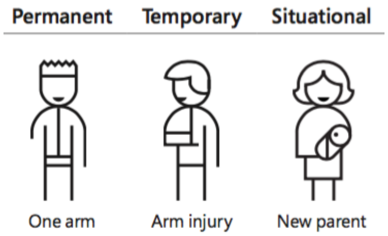
Fig.5 Aging -in-place Spectrum Diagram

Disabling aging in place through architecture

What often goes unrecognized to many architects is that we all fall victim to the exclusions our buildings create. With age, we all begin to lose abilities and change, experiencing challenges to inhabit our built environment. The most prevalent ramification is the inability to 'age in place'. 'Aging in place' is when a person lives in a residence of their choice for as long as they are able to as they age .[15] Despite connotation, we are all actively aging in place, and there is no set age to when you begin to 'age in place' (Fig.5). The main benefit and desires of aging in place is the ability to maintain their quality of life by preserving their independence and lifestyle in a community of their choice.[16] Any assisted living programs such as long term care or nursing homes are not forms of 'aging in place' because the individual's daily life is controlled and scheduled by the institution. While the majority of seniors in Canada expressed desire to age in place, there is still an extensive wait list for senior residences .[17] However, it is estimated that one third of residents at long term care homes were prematurely admitted, where they only required low to moderate needs and could have aged in place if environmental needs were initially met in their homes[18]. The repercussions of early entry into nursing homes despite the wishes of the user have repeatedly proven to lead to depression, social isolation, and even early death. [19] Yet despite all evidence, there is still a lack of interest and effort in architecture to research and explore how architecture can better accommodate aging in place.

How architecture can enable

If environments have the power to disable users, they also have the power to enable them. Designer Susan Goltsman defines 'inclusive design' as a process and philosophy that believes the abilities of users are determined by the design of their environments. [20] The main principal of inclusive design is to enable all users to the same degree by creating diverse ways to use the environment and widen the spectrum of accessible users. [21] Contrary to universal design's method of finding commonalities in all users to create a design that fits most, inclusive design addresses those who are most different and focuses on how to resolve their specific challenges, increasing accessibility one group at a time. [22] Thomas Carpentier's "Measure(s) of Man: Architect's Data Add-on" project, for example, demonstrates how designing specific architectural elements that cater to unique user needs supports abilities that would be typically disabled with standard generic architectural designs [23] (Fig.7). While the project might not be the most efficient or cost-effective method to achieve these abilities, it nevertheless showcases a unique opportunity for architecture to enable more of our users. Through design, environments can not only house our daily activities, but can also push boundaries of what is possible for the user, whether it is regaining lost abilities or supporting current ones. Inclusive design is a human centric design approach that allows marginalized users to identify design problems and also guide the solution for designers .[24] Specifically designing for a marginalized group both guarantees accessibility for them and improves use for people not in the group but



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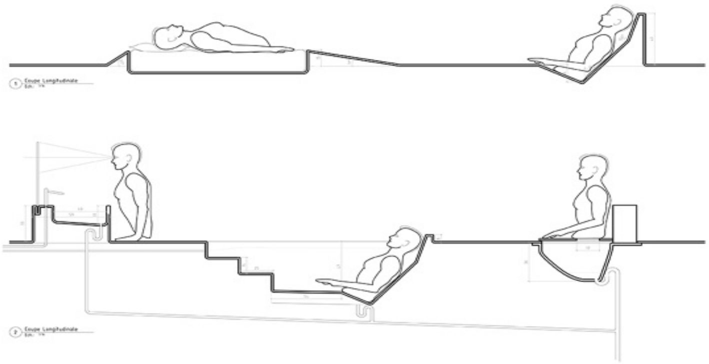

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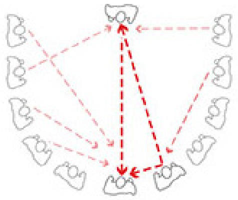


Fig.8 U-shaped podiums designed to allow front row view for every student for easy sign language, *The DeafSpace Project* by Gallaudet University, 2005

experience similar challenges. [25] Many designs with the intent to gain ability for the disabled also advance the abilities for those who are not. The typewriter was first created for the blind to enable them to write, however this innovation propelled all human abilities to write, transfer, and record information faster and more efficiently than before. [26] Jos Boys, an architectural disability author, points out that this is a huge merit in designing for disability, where the unique perspectives and challenges that people with disability face have the potential to bring insight in generating design innovation in architecture for all .[27] A prime example is the project Deafspace by Gallaudet University, who developed the campus specifically to accommodate deaf student needs but soon recognized that these design qualities appealed to everyone (Fig. 8). [28] Like this, designing for aging in place not only applies to all of us, currently and in the future, but also has the potential to improve architecture for all of its users. Using the design approach of inclusive design, challenges of aging in place can be identified as design problems to initiate and guide design intervention.

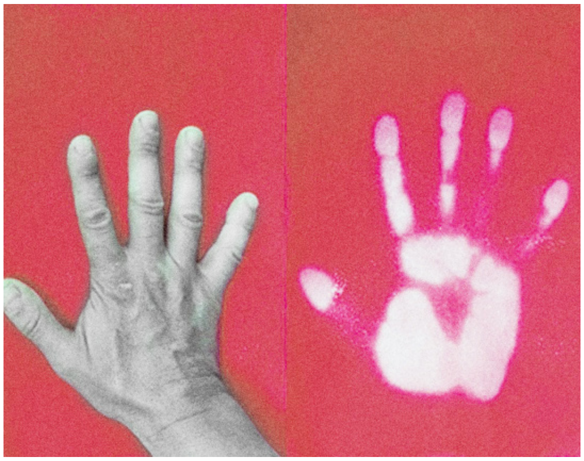
What might an environment that enables aging in place look like? And more specifically, how might we supplement our lost abilities through architecture?

Smart materials

A key set of abilities we lose with age are those that help us respond to conditions of our environment, atmospheric changes such as temperature[29] and lighting[30]. As these conditions are always in fluctuation, our response is also dynamic and ever changing. To translate these human behaviors through architecture requires our environments to gain dynamic abilities closer to the human, adapting and responding to the changing conditions of their surroundings. This thought of adaptive[31] or responsive[32] architecture has been conceptualized before, in the past often to allow environments to take on multiple conditions to accommodate changing programmatic spatial needs of the occupant[33]. For example, Rietveld's Schröder house allows users to customize their home to meet their daily needs through sliding and folding partitions (Fig.9).[34] Project by DSR, The Shed, allows flexible event spaces through its telescoping outer shell that deploys over the public square for indoor events and nests over the building for outdoor events (Fig.10).[35] Our current era with its unique technical abilities, however, presents potentials beyond the past in this arena. As advancements of technology, digital fabrication and smart materials permeate architecture, new abilities of our built environments are emerging, where they are becoming more alive, equipped with abilities to sense and respond to their changing surroundings. Smart materials are of importance here; these are materials that can sense and react to external stimuli in a predictable, often physical, manner. [36] These materials are not limited to a scale, or whether they are a singular, composite, or a system of materials. [37] Their innate dynamic mechanisms allow them to move without the need for complicated controllers or interfaces like their electromechanical counterparts[38]. This unique characteristic also allows systems of smart materials to freely vary scale and resolution of interaction, enabling highly discrete

Fig.9 *Rietveld Schröder House* by Gerrit Rietveld, 1924 [Centraal Museum collection, Utrecht, Stijn Poelstra]

Fig.10 *The Shed* by Diller Scofidio + Renfro, 2019



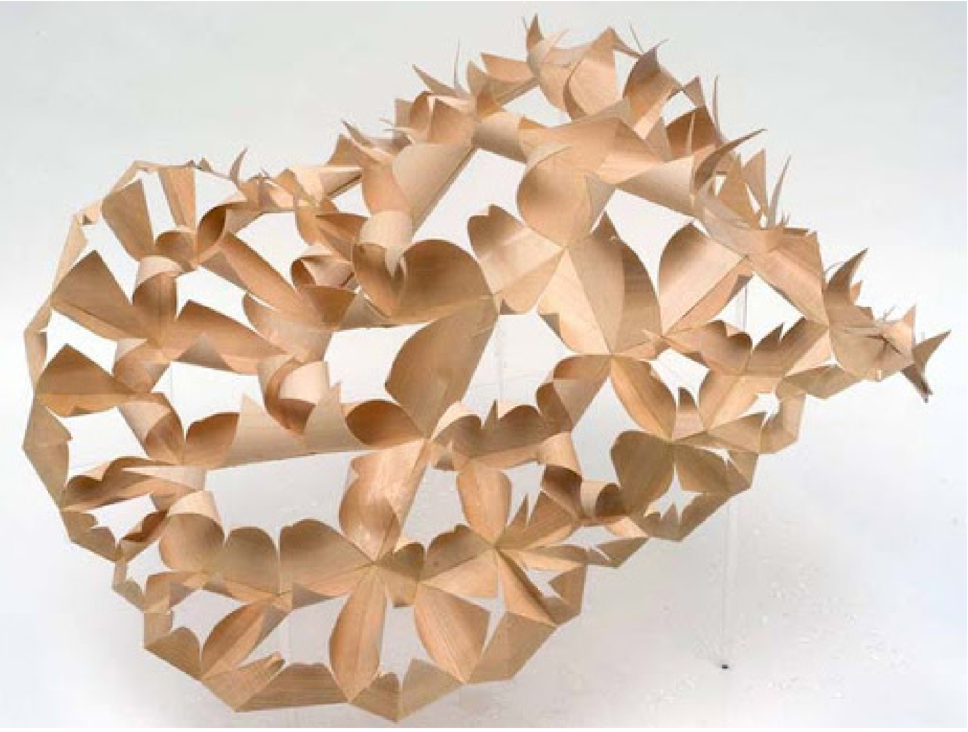


Fig.11 Bottom: *Responsive Surface Structure II* using hygroscopic wood by Steffen Reichert [HFG Offenbach University of Art and Design, Germany, 2008]

Fig.12 Top : Thermo-chromic paint leaving hand print, edited by author [CöLöRs]

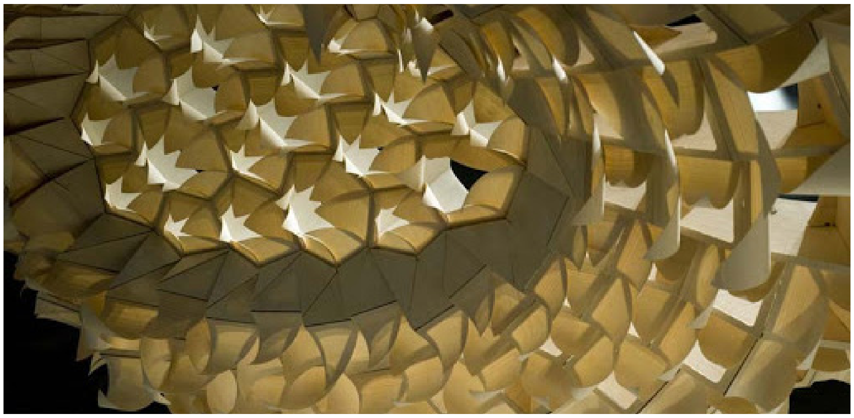
responses. Resolution here means the degree of stimulus sensitivity that the system can respond. For example, the resolution of a hygroscopic wood veneer system can increase simply through cutting smaller strips of the veneer, as the material itself carries innate abilities to sense and react (Fig.11).[39] Furthermore, materials such as thermo-chromic paint, have a resolution at the molecular level where each particle can change color with temperature (Fig.12). The scalability of smart materials makes them valuable interfaces for interactive systems between the occupant and the building as they can respond both at the larger scale of the environment and at the scale and resolution of the individual.

Due to their expensive and experimental nature, however, smart material application in architecture is often limited to realms of research and art, and commercially found mostly in one-off luxury projects. Additionally, existing smart materials in architecture carry preconceived notions of their utility, narrowing their scope of application to only serve very specific needs and proposes. For instance, an early architectural application of smart materials is the Bloom pavilion by DOSU Studio, where a material called thermobimetal created an autonomous shading system that opened and closed with changing sunlight conditions (Fig.13).[40] Since then, architects have continued to explore smart materials like wood, shape memory metal alloys, and shape memory polymers, mainly for façade applications that interact with exterior conditions for human comfort and energy efficiency.[41] Michelle Addington, an author and researcher of smart material applications in architecture, points out that the main issue of smart material application in architecture is a lack of understanding of their instrumentality and behaviors:

> *"Knowing how the material works, however, is not the same as knowing how the material should work. The opportunities posed by smart materials are not so much about the actual materials or products themselves, instead it is their instrumentality that we should be exploiting... Fundamentally, the behaviors are what matter and we should recognize that we can produce our desired behaviors from a multitude of materials, including the conventional. Smart materials may simplify the system, but we are unlikely to encounter a need that cannot be met by conventional materials and technologies. The true opportunity to be gained from smart materials arises from how they are used, not what they are."* [42]

Fig.13 Top: *Bloom,* thermobimetal sun shading pavilion by DO|SU Studio Architecture [Alison Furuto, 2012]

Fig.14 Bottom: *Hygroscope: Meteorosensitive Morphology* by Achime Menges in collaboration with Steffen Reichert, 2012



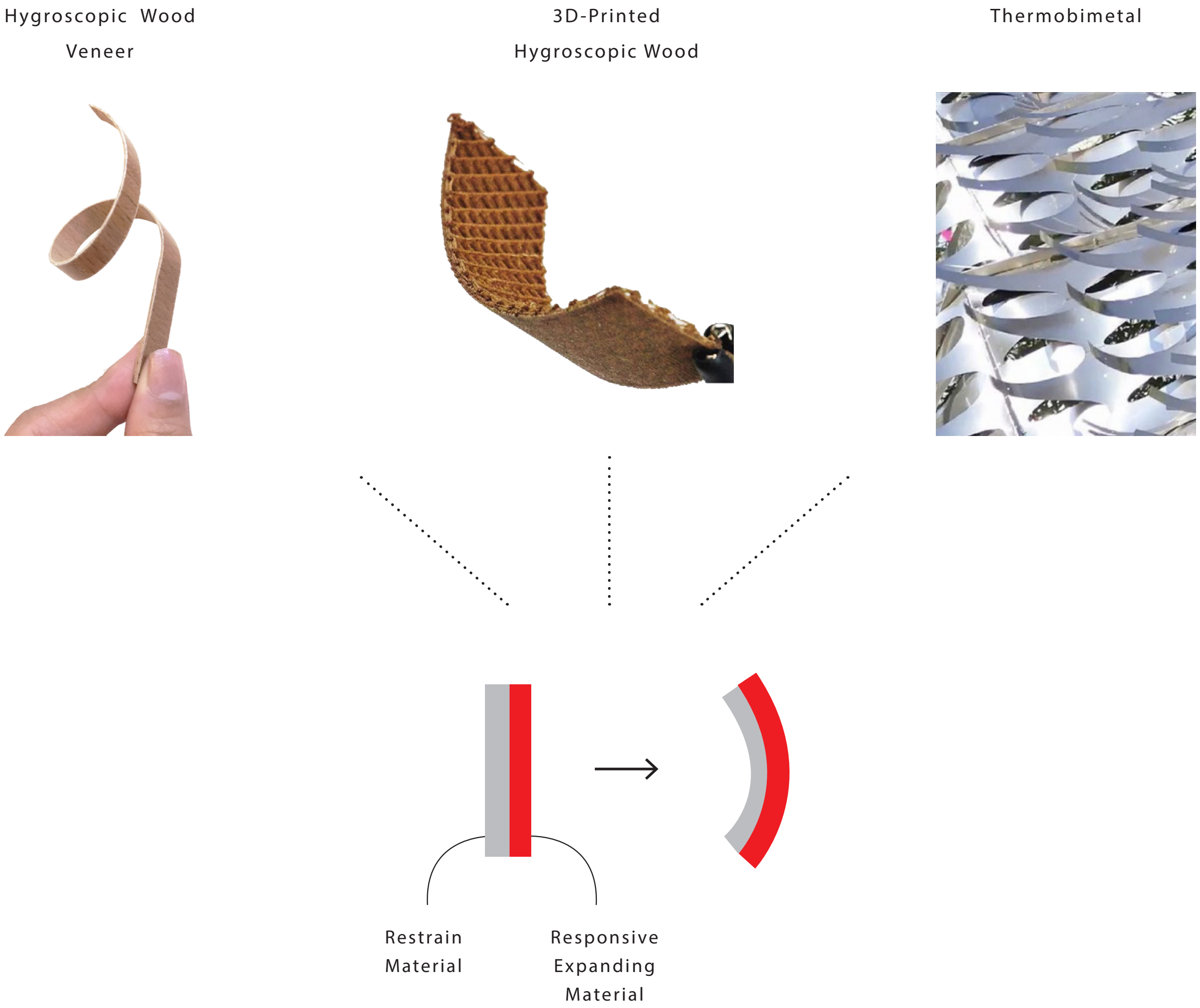


Fig.15 Diagram shows how the bilayering strategy- a method where two different materials that expand at different rates under a stimulus results in a dynamic curling effect, has been adopted with different materials to create various smart materials with similar behaviors. [Illustration by author; edited from David Correa, 2015; Alison Furuto, 2012]

In understanding and recognizing what smart material properties make them dynamic and responsive, we expand our ability to manipulate smart materials that fit our desired applications. The properties observed can become key references in creating similar smart material traits across scales as well as different materials, allowing their application to be more flexible and feasible (Fig. 15). To effectively use smart materials in our environments, architects must not only design the architecture they apply to, but also must design how the materials are applied, harmonizing between space and the material behaviors for their desired effects. Using the methodology developed by Addington and Shodek of smart material application in architecture, I design and facilitate the behavior of smart materials to alleviate challenges of aging in place.

Fig.16 2D shape self-morphing into 3D ball in response to water, *4D Printing: Tuncated Octahedron* by Self-Assembly Lab, MIT+ Statasys Ltd+Autodesk Inc.

Transferring human abilities through Smart materials

With recent advancements of digital fabrication tools achieving higher precision and capabilities like multi-material printing, we have propelled abilities to manipulate smart materials for our desired functions[43]. Within this advancement, many researchers are beginning to utilize smart materials to transfer and replicate human functions to our environment, giving smart materials abilities to be almost with intelligence, acting with purpose. Work by research group led by Skylar Tibbits, Self Assembly Lab, designs smart materials to mimic human actions like constructing or assembling parts, allowing for autonomous building [44] (Fig.16). Works of David Correa et al, demonstrates smart materials' programmability, whereby allowing us to discreetly program their dynamic behaviors to act with purpose, we can transfer human ability to reason (Fig.17).[45] Neri Oxman and Mediate Matter Lab, have explored biomimetic materials of the human body and applied them for larger construction in the environment, allowing architecture to replicate the physical properties of the human body such as human bone structures (Fig.18).[46] With these developments, designers are also finding new applications for smart materials, where they enhance human abilities through various scales. A project by Tangible Media Group at MIT called Biologic showcases a sweat responsive suit that opens and closes, enhancing thermal regulation for the wearer [47](Fig.20). At the architectural scale, smart material applications have shown to aid human inhabitation by creating environments that are active participants in changing and adapting to user need. The Lumen project by Jenny Sabin Studio uses knit fibers that respond to changes in the environment such as heat, light, and human interaction[48]. The project works in a system of smart materials and sensors to change its environmental conditions throughout the day, adapting to provide ideal climates for the occupant [49](Fig.21). The breadth of new smart material application explored showcases that architecture can become an active agent in interacting with their occupants to provide ideal conditions for comfort and desire. However, in this exploration, what we have missed is the opportunity for smart materials to create environments that aid and supplement the abilities of marginalized user groups. Using smart materials' capability to automate, program, mimic, and interact with users, architecture could adapt to the

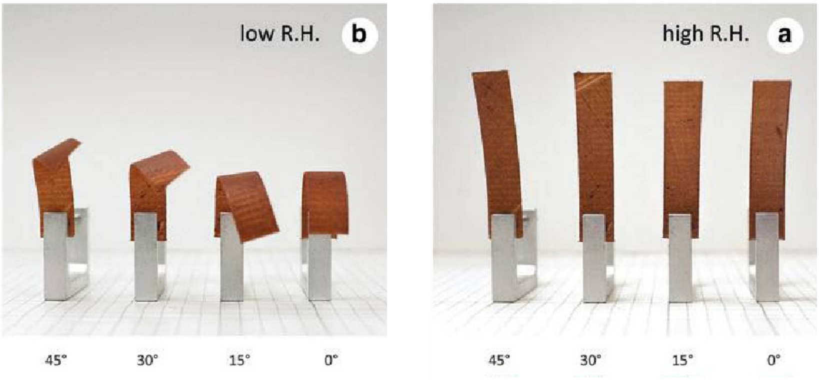


Fig.17 Top: *3D printed Hygroscopic Programmable Material Systems* by David Correa, 2014

Fig.18 Bottom Left: *Monocoque 2*, a structural skin prototype using voronoi pattern resembling of bone tissue structure by Neri Oxman, 2007

Fig.19 Cancellous (Spongy) bone in human femur [edited by author, original by Richard Owen, 1866] needs of people with disabilities to enable them equal and enhanced accessibility in our built environments. For aging in place, smart materials can become vehicles to transfer our lost responsive abilities to our environments, allowing architecture to respond for us as we age. Our homes could become equipped with similar response systems to humans and aid us in adapting to their changing conditions, providing us the tools to inhabit them better.

Scope

In this regard, the thesis designs smart material applications in architecture that address challenges of aging in place. It takes on an exploratory approach to design research, exploring the intersection between the fields of smart material and inclusive design in architecture. This thesis investigates the role of smart materials in creating supportive interactive relationships with users by focusing on the constraints of aging in place. I develop three design experiments, each beginning with a specific challenge to aging in place and followed by a smart material design intervention to address it. Through an iterative and experimental, hybridized user and material-oriented design process, a design methodology is generated in applying smart material technologies for inclusive architectural design. The three design experiments demonstrate the potential for intersecting fields of human centric design, smart material design, and digital fabrication to enable users.

In the context of the thesis, the 'home' consists of any place of living outside of assisted-living institutions. Only conceptual representations of typical programs that exists in a 'home' such as the living room, bedroom, and bathroom, are used to create a generic field of investigation. Therefore, while the goal of the thesis is to create designs that aid in prolonging aging in place, the design applications also have the potential to be applied to any type of living. While the thesis does not engage investigations beyond the user group of seniors and the smart materials it adopts, it nonetheless positions the potential of these investigations in addressing different users, smart materials, and user interactive systems.

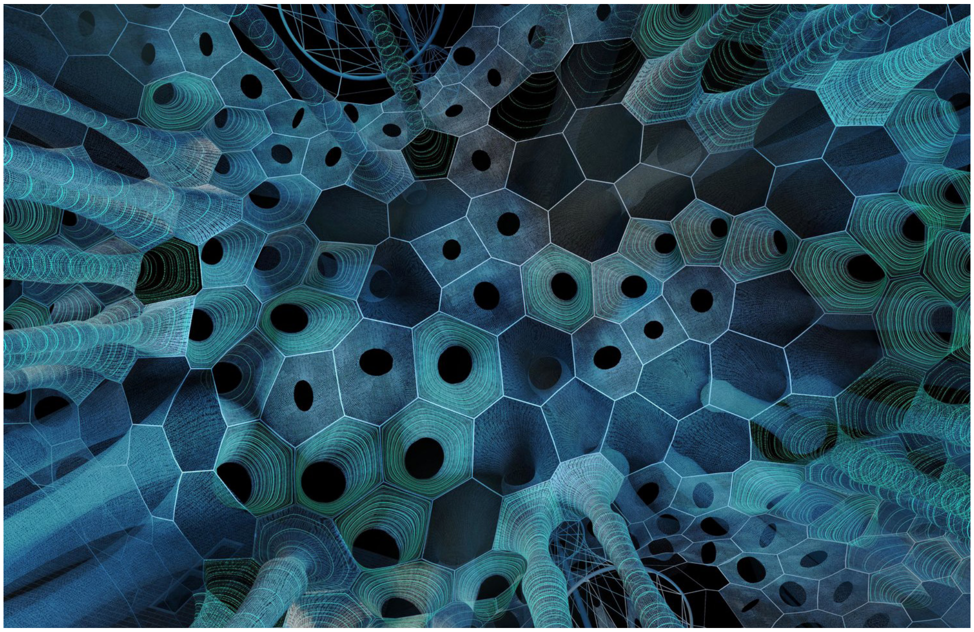


Fig.20 Top: *bioLogic*, sweat (moisture) responsive apparel made from Natto bacteria using expansion and contraction of its cells, by Lining Yao et al, 2015 [Tangible Media Group , MIT]

Fig.21 Bottom: *Lumen*, a responsive textile structure displaying glowing light in darkness, by Jenny Sabin Studio, 2017 [Pablo Enriquez, Yuriy Chernets]

Design Approach and Methods

The thesis takes on two main design approaches to inform and guide the design experiments. First, a human centric approach to design guides in contextualizing and identifying design problems of aging in place to initiate the design process. Second, a material-oriented design approach informs in designing of smart material applications that alleviate challenges of aging in place. Analysis and observations of existing smart materials act as key drivers in designing their dynamic behaviors for application. The two design approaches together inform an iterative design through making that results in proof-of concept prototypes for the design experiments. The methodology of the thesis, therefore, consists of three sequential parts, each influenced from its respective approach and field, creating a hybrid of qualitative and quantitative research methods (Fig.22):

Part One: Identifying Challenges of Aging in Place,

Identifies design problems of aging in place through qualitative analysis of aging in place. Open-source data sources such as public reports, research journals, and open help forums, help create unbiased contexts and identifications[50]. Hacks used by seniors are surveyed to identify tangible moments in the environment that act as obstacles to aging in place. The goal of this step is to extract focused points of challenges in aging in place and use them as sites of design experiments.

Part Two: Application of Smart materials,

Analyzes the sites of design experiments in detail, investigating the physical aspects of the body that led to the challenge within the environment while aging in place. Analysis of the body's response to challenge conditions informs a nuanced understanding of what response systems are lost with age and how it leads to the challenge in each design experiment. This information guides the design of the behavior of smart materials, laying out the required response functions and parameters. Then, smart materials that show best potential in actuating these behaviors are chosen through a critical survey of their properties, within a pool of existing smart materials. A comprehensive understanding of smart material properties, as well as the desired response, is analyzed and explored in this step of the process. A preliminary design concept for application of the material is generated.

Part Three: Prototyping,

Consists of iterative design through prototyping, cumulatively informed by both the user and the material. Through iterative cycles between prototyping and designing, a proof of concept design and prototype are developed:

Experiment 1 : Auxetic suit: lightweight and form fitting protective apparel.
Experiment 2: Hydro Floor: a water responsive floor system that enhances grip and indicates wetness.
Experiment 3 : Breathing Façade: heat and humidity responsive screen system that allows environments to thermally self regulate.

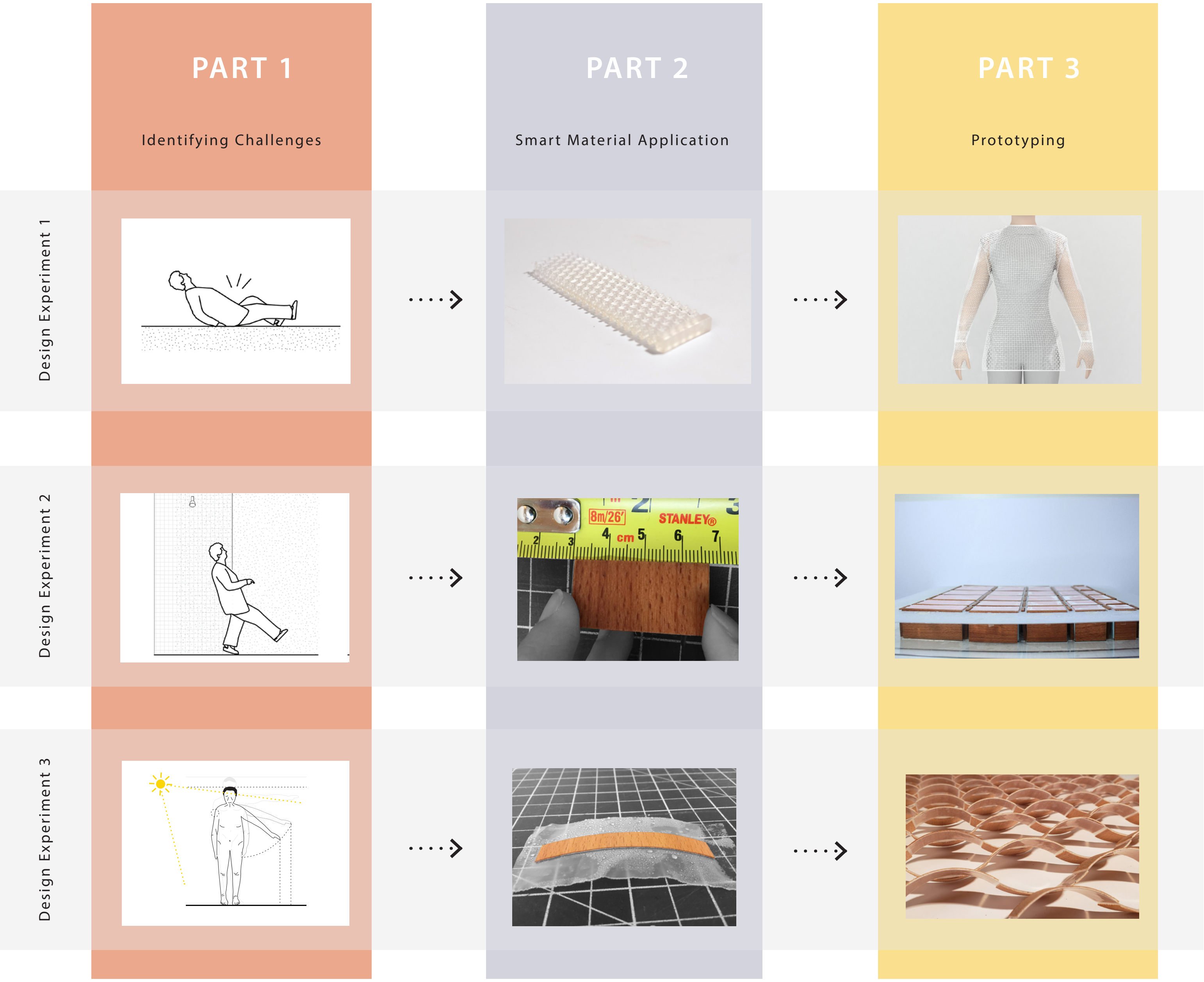


Fig.22 Thesis Organization Structure Diagram

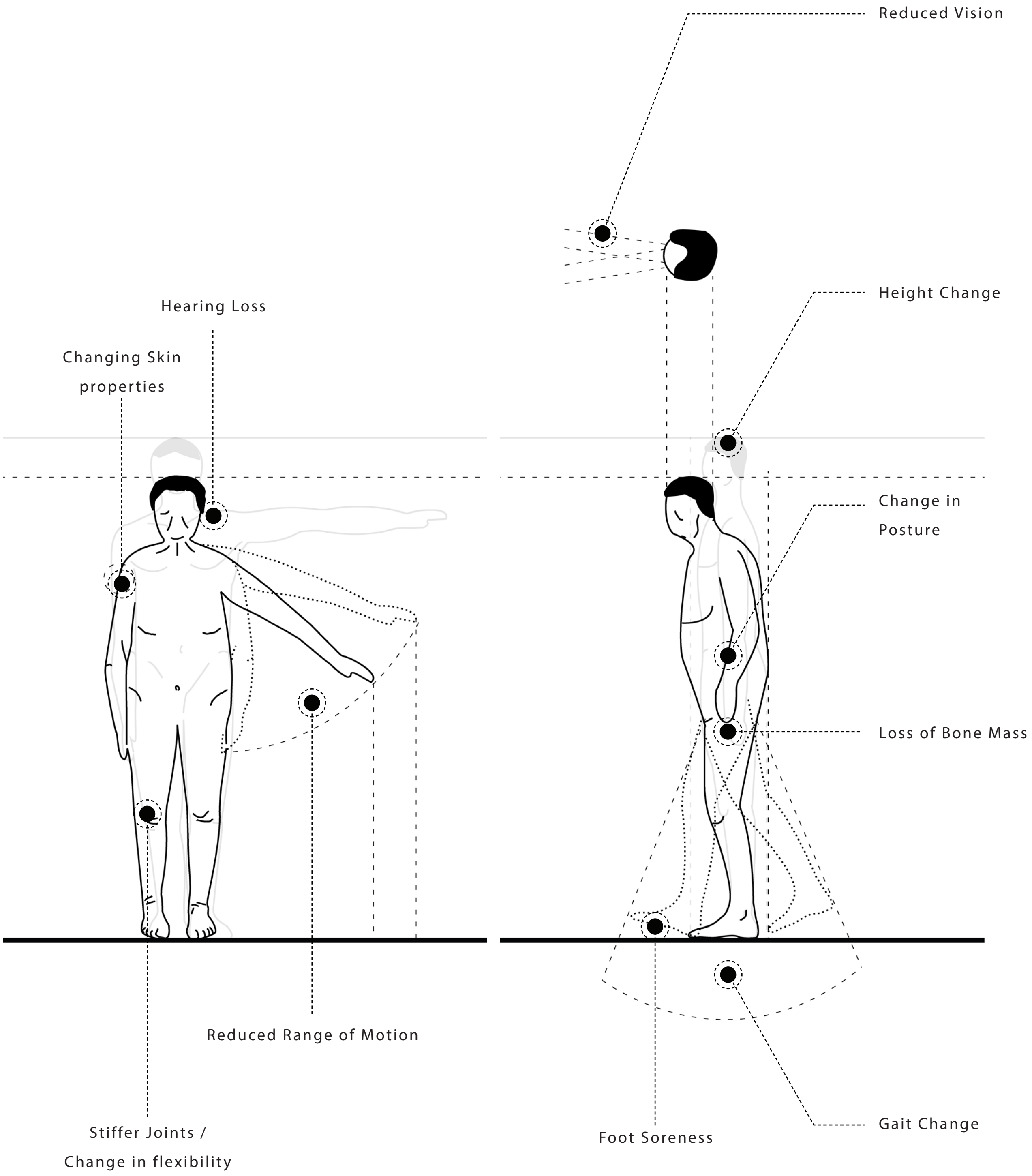


Fig.23 Diagram of changes in the body through aging

Part 1 : Identifying Challenges of Aging in Place

As a result of illness or physical deterioration, different misfits between users and their environment may appear suddenly when aging. It might come in the form of a chair that is no longer comfortable or accessible, or a doorstep that is too steep. These misfits occur all around us and are hard to predict and prevent before they appear. Therefore, many seniors use 'hacks' to mend these conflict areas. Hacks are what I call small furniture pieces or architectural prosthetics commonly used by seniors to support them in their homes. Hacks vary in scale from prosthetics on the body to prosthetics on the built environment, but their main use is to bridge between the user and the environment to enable accessibility for the user. Some common examples are handlebars installed in bathrooms, anti-slip mats, and ramps on steps. While these hacks appear effective, they are only band-aid solutions and they do not provide preventive measures for future incidents. Glen Hougan, an industrial design researcher at the Mayo Clinic, however, discovered that observing hacks provided valuable insight into the affordance and needs of seniors. He noticed that most seniors customized or invented new hacks of their own that better met their needs then of those designed by designers (Fig.24).[51] Through observing these modifications and designs, he realized that they self-revealed weak points in the designs, allowing designers to gain user feedback as well as identify new design problems.[52] Human centric design principals view identifying the design problem as the most essential step in creating designs that directly meet user needs.[53] In architecture, the wide-spread use of hacks by seniors can provide design problems at the larger scale, illuminating points of misfits within the home while aging in place. The hacks, therefore, identify various parameters useful in initiating the design experiments

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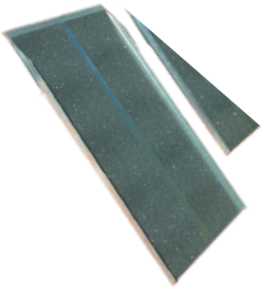

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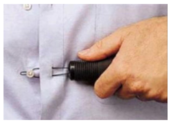
Fig.24 Catalog of common hacks used by seniors while aging in place, reformed & commercial objects

(a) Walker with tennis balls for higher stability/ traction
(b) Reformed Ice pack turned into back pack for easy-use
(c) Ramps to put over stairs
(d) Reformed chair with shelf grip liner for better traction on seat
(e) Lift support handle bars
(f) Doorknob extender
(g) Handy Grabber
(h) Button Helper
(i) Reformed handheld items with gauze to enhance grip
(j) Multiple anti-slip mat for varied grip
(k) Urination Help Device
(l) Lift Chair Recliner
(m) Reformed drawer handle with rope for better grip
(n) Dressing Stick
(o) Light Switch enlarger
(p) Reformed Apron turned heatpack for easy-use
(q) Shower chair
(r) Light Switch Labels
(s) Key Handle enlarger
(t) Positioning Mat
(u) Shower Grip Handle
(v) Extended Shoe horn
(w) Stair chair lift
(x) Pill Dispenser
(y) Reformed cane handle with rope for better grip
(z) Car seat lift handle



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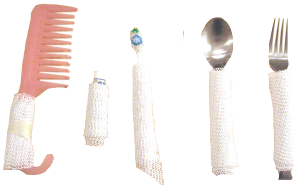

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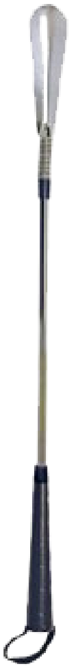

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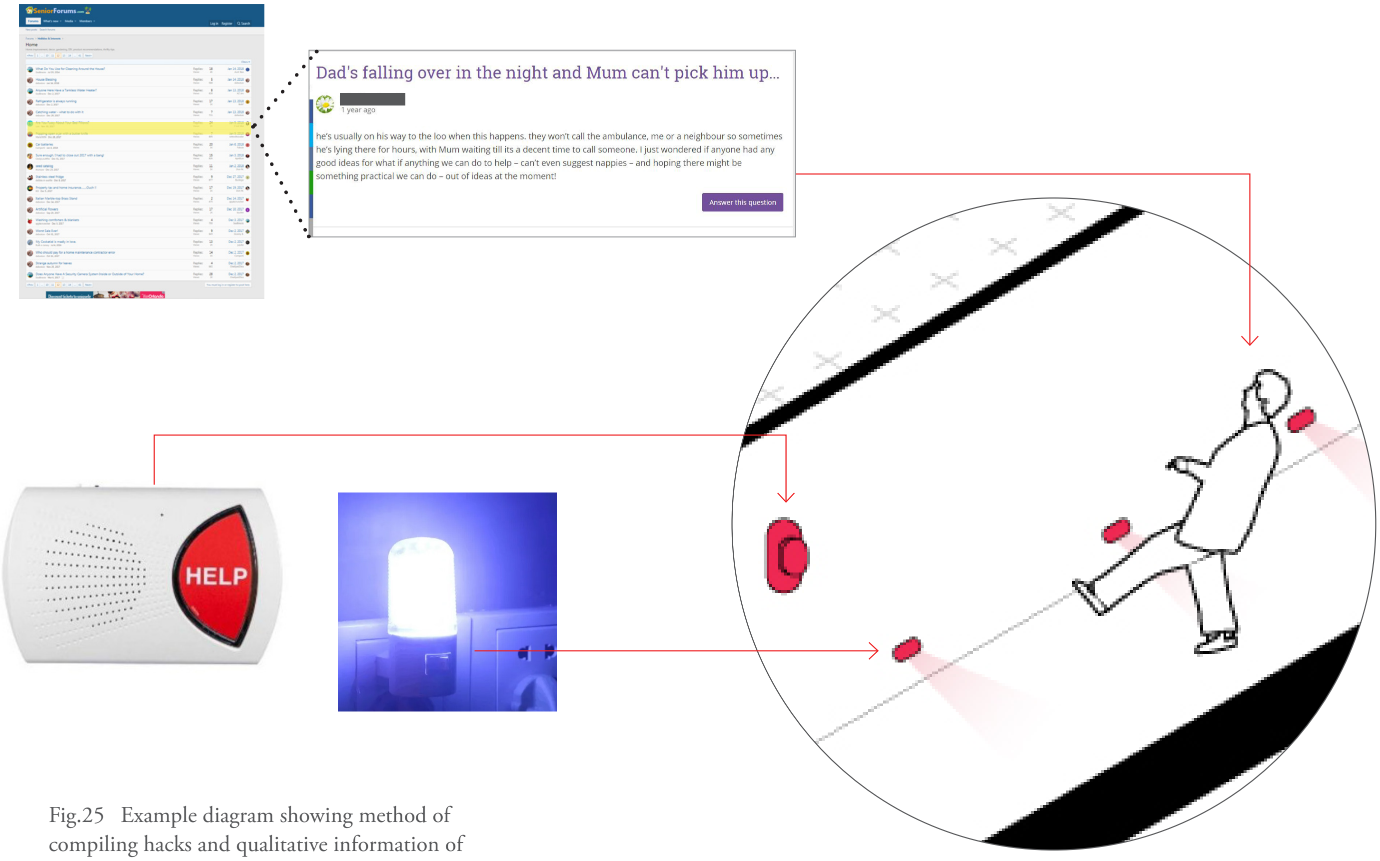
for the thesis. Firstly, the location of the hacks allows us to pinpoint tangible areas in the home that present challenges for seniors, providing potential sites for design experimentation. Secondly, the functionality of the hacks indicate what specific challenge exists and what kind of solution is required in the given location. Lastly, through qualitative research through open source databases such as help forums, the user can be situated in the challenge moment providing a nuanced picture of why the challenge exists (fig 25).[54] Understanding the social and physical context of the problems that motivated the hack allows the designer to evaluate existing designs of hacks and find alternative solutions that are more permanent and better integrate into the built environment. Specifically, looking at how the hacks were unsuccessful for the user provides great insight in how to further improve the design and better meet the affordance of the user.[55] Therefore, by focusing on specific moments, the bigger problem of 'aging in place' is broken down into individual design problems more manageable for a designer. The design process developed from addressing individual problems then act as a framework to address other challenge moments, allowing them to collectively tackle the larger problem of aging in place. Three design problems identified by hacks were chosen to initiate the design experiments for the thesis: falling, slipping, and thermo-regulation.



Dad's falling over in the night and Mum can't pick him up...

[redacted]
1 year ago

he's usually on his way to the loo when this happens. they won't call the ambulance, me or a neighbour so sometimes he's lying there for hours, with Mum waiting till its a decent time to call someone. I just wondered if anyone had any good ideas for what if anything we can do to help – can't even suggest nappies – and hoping there might be something practical we can do – out of ideas at the moment!

Fig.25 Example diagram showing method of compiling hacks and qualitative information of aging in place challenges

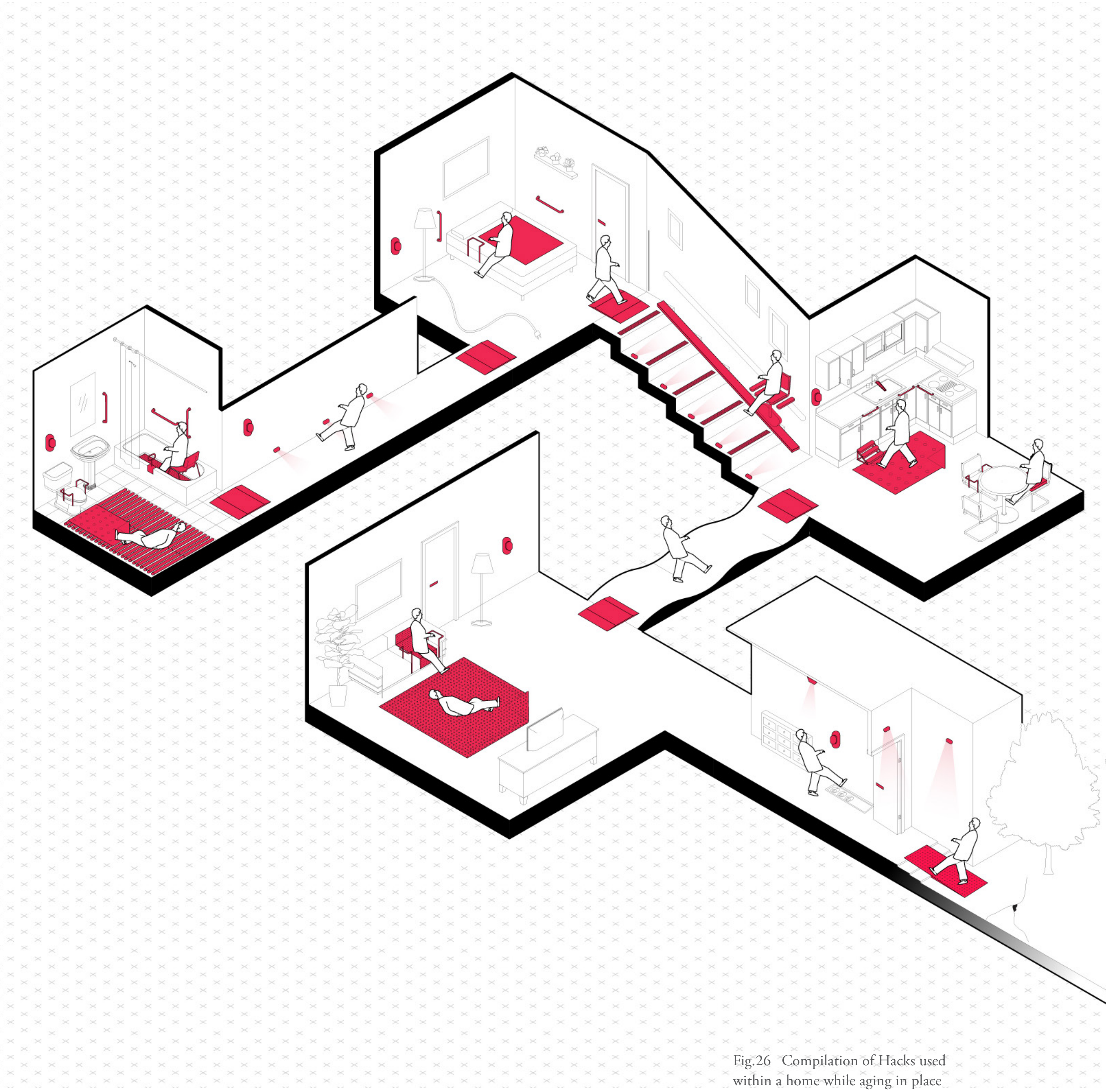
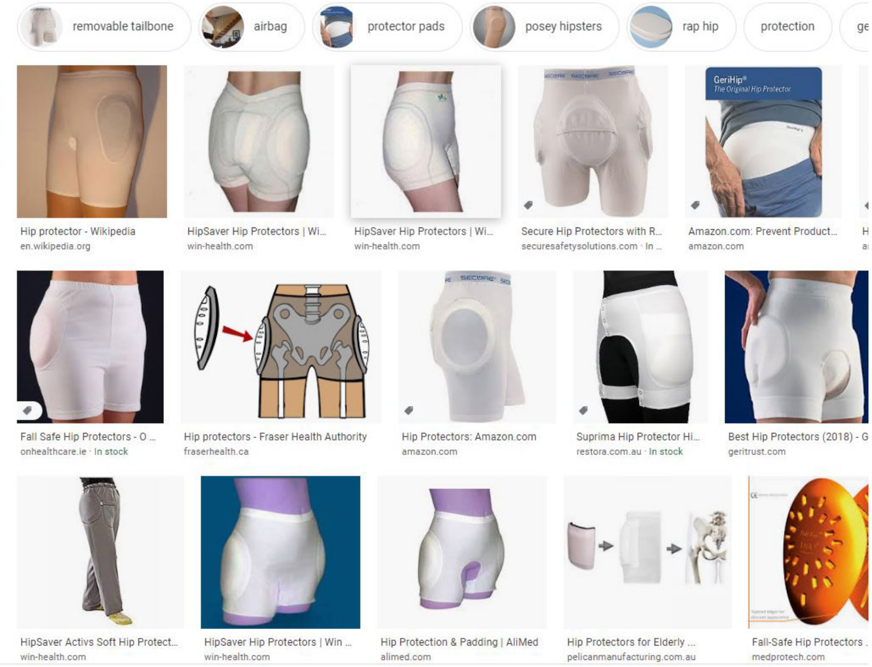


Fig.26 Compilation of Hacks used within a home while aging in place



Design Experiment 1: Falling

Falling is the leading cause of injury-related hospitalizations amongst seniors in Canada and remains one of the highest health concerns amongst aging in place for seniors.[56] The most common 'hack' to prevent injuries due to falling is protective clothing such as hip pads (Fig.27). Hip fractures are one of the most detrimental injuries from falling for seniors, where almost half of patients with hip fractures are unable to return to full independence and require aid for their daily activities.[57] Despite these serious known risks, acceptance and use of hip protective wear is low, and remains the largest obstacle to their effectiveness.[58] Qualitative studies show that most frequent reasons for not wearing hip protectors are: discomfort due to fit, over heating, and extra time/effort required to wear hip protectors.[59] Moreover, the appearance of hip protectors is also a significant factor in the decision to wear hip protectors.[60] Design Experiment 1, investigates the causes of falling amongst seniors and explores a smart material application that can alleviate injuries from falling while addressing the obstacles of existing protective wear.

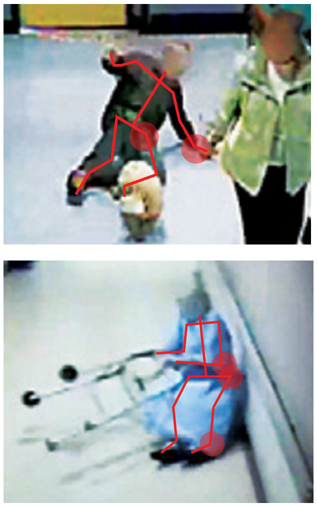


Fig.27 Top: Common Elderly Hip Pads. [Google image search, elderly hip pad Aug. 2020]

Fig.28 Bottom: Diagram of impact points on the body during a fall [edited by author, Elsevier, The Lancet, 2013, License number : 4891660169690]

Design Experiment 2: Slipping

Factors of falls in seniors are often divided by researchers to two categories: intrinsic and extrinsic factors.[62] Intrinsic factors include individual circumstances such as muscle weakness and vision impairment, that increase the chance of falling for seniors.[63] Extrinsic factors include environmental risks that may cause slipping and falling such as slippery floor surfaces, obstacles, and poor lighting.[64] Design experiment 2 focuses on an extrinsic factor of falling: slip prone floor surfaces.

A common hack used to prevent slipping includes additional floor coverings such as anti-slip mats or pads that create greater traction for slippery surfaces. These devices typically create traction through surface textures such as raised ridges or bumps that allow for greater grip (Fig.29).[65] While these floor mats are convenient due to their quick and non-invasive installment, research shows that when not properly adhered to the floor, they are hazardous and provoke falls themselves.[66] An average of more than 11 rugs without proper nonslip backing were found in homes of seniors, which can result in slipping of the mats as well as curling, becoming tripping hazards. [67] Moreover, during an informal observation of a home of a senior aging in place, I found that anti-slip mats were inefficient as multiple mats were required to provide different grip requirements for different purposes (Fig.30). In response to these hazards, Design Experiment 2 explores a holistic grip system integrated into the design of a floor that effectively mitigates slip-prone spaces of the home.

Fig.29 (Bottom): Common textures used for traction

Fig.30 (Top): Multiple grip mats are used to provide varied traction for different areas of the washroom.

Design Experiment 3: Thermo-regulation

Climate change is predicted to increase extreme weather conditions such as sustained heat waves across the world.[68] In the past 20 years, mortality rates due to heat waves have increased especially within senior populations .[69] During the European heatwave in 2003, approximately 70,000 people died of heat-related illnesses, where more than 50% of deaths occurred in homes.[70] Research shows that seniors, particularly over age of 60, are more susceptive to heat-related illnesses as our abilities to thermoregulate decline with age.[71] Current thermo-regulation systems include smart thermostat technologies that automatically regulate temperatures of the home, some even precisely controlling temperatures based on daily patterns.[72] While these technologies are great thermoregulators for air temperature, it is limited in control of other climatic parameters such as radiation and humidity that greatly determine the body's temperature.[73] Sunlight control is an important factor in regulating interior temperatures and requires more localized regulation as conditions change over the course of the day. A typical method of controlling solar-heat gain is sun-shading systems such as interior blinds that the user can open or close depending on need. With age, however, our bodies begin to lose ability to sense heat, making a self-controlled blind system not as effective for seniors. [74] Alternatives like automatic blind systems, however, are expensive and energy intensive. Responding to humidity is also an important factor in thermal comfort because it determines what actual temperature feels like. The cooling mechanism of our bodies rely on the evaporation of sweat; therefore, as our environment becomes more humid, our ability to regulate heat is compromised because sweat would evaporate at a slower rate. Hence, when the environment is more humid it feels hotter and when it is drier it feels colder. Design experiment 3 investigates a passive shading façade system that thermally self regulates, controlling sunlight and humidity conditions.

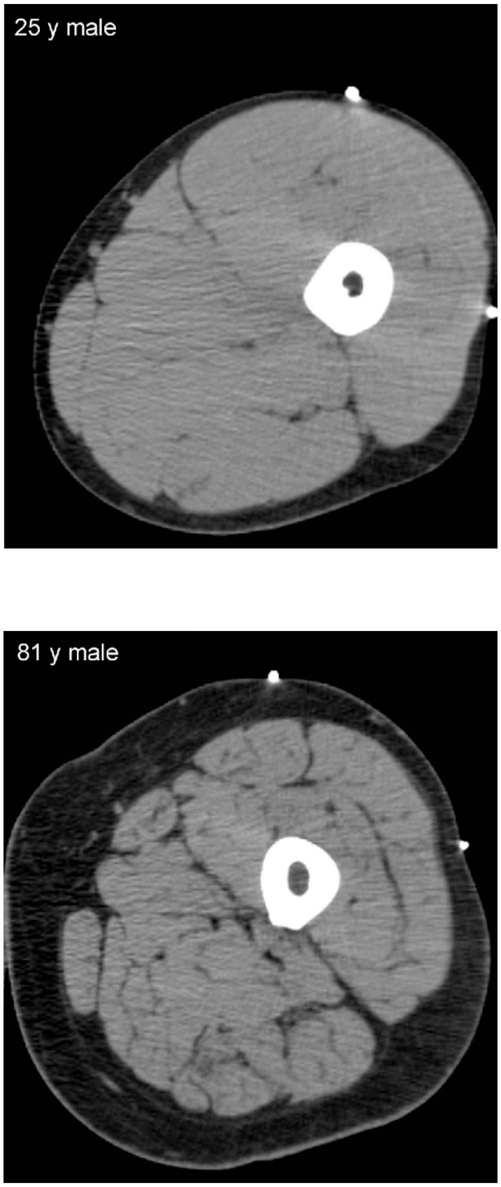


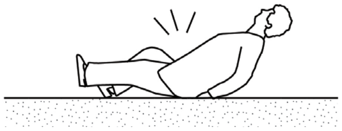
Fig.31 CT Scan of mid-thigh, grey represents the muscle (top) 25year old male (bottom) 81 year old male. Reduction of muscle area can be noticed on the older male.
[René Koopman, L. J. C. van Loon , 2008]

Design Experiment 1:

Auxetic Apparel

Anatomy of Falling:

When we fall, our bodies respond through the muscle to absorb and distribute the force of impact, protecting our bones.[75] Hence our muscles often automatically flex before impact to increase the volume the force must travel through.[76] With age however, our bodies increasingly lose muscle mass, decreasing our ability to lessen the impact of falls (Fig.31).[77] Moreover, with decreasing bone density as well as reduced bone formation, falls become more detrimental through age, leading to more severe injuries such as hip fractures and longer recovery time.[78] In addition, health conditions such as muscle weakness and vision impairment make us more prone to falling as we age, increasing the chances for injury.[79] Precedent analysis prior shows that current available protective wear fall short in comfort, appearance, and convenience of wear. The following proposed approach therefore aims at maximizing comfort through flexible formfitting materials, while creating a unified system for protecting multiple points of the body holistically for efficiency and convenience.



Smart Material Application: Auxetic Material

Similarly, to how our muscles respond to force by flexing, a smart material type called auxetic materials act in a similar way, except instead of expanding on impact, they contract proportionally around areas of pressure.[80] By contracting upon impact, auxetic materials absorb shock by distributing force throughout the structure as well as densifying the material at the point of impact[81]. The material's dynamic structure therefore allows for greater shock absorption while using less volume of the material itself[82]. Any material that has a negative Poisson ratio is identified as an auxetic material, meaning that unlike common materials that become perpendicularly thinner under pulling forces (tension), auxetic materials expand in all directions when pulled, and contract in all directions when compressed (Fig 32).[83] This property is achieved through the material's structure rather than chemical properties.[84] Therefore, auxetic properties can exist in various scales from the microstructure of the material to large structures made up of assembly of materials.[85] Additionally, when an auxetic structure is made of flexible materials that can form one directional curvature, the auxetic adopted material then can form double curvatures such as domes, a property called synclasticity (Fig.33).[86] Due to these material qualities, auxetic materials have found applications for various protective use such as on military armored vehicles, helmets, and body armor for sports (Fig.34).[87]

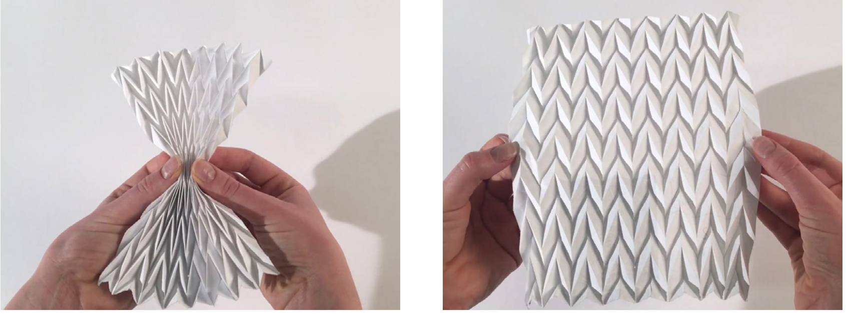


Fig.32 Top: Auxetic prototype demonstration of Negative Poisson's Ratio behavior

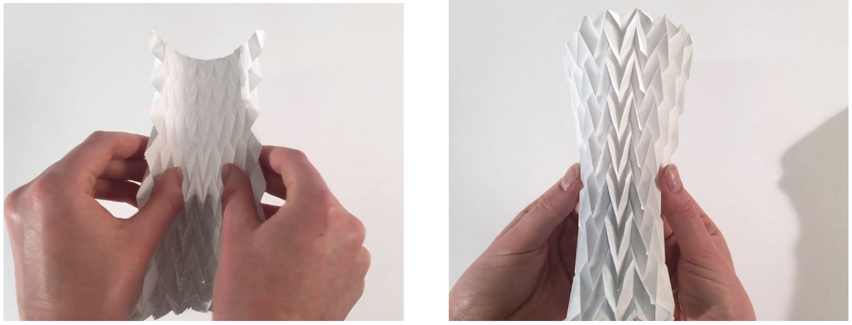


Fig.33 Bottom: Auxetic prototype demonstration of synclasticity behavior

a. Auxetic Foam for sport safety devices

b. Auxetic expanding clothing for children

c. Auxetic Interactive Inflatable Installation

d. Lightweight auxetic composite panel enhancing ballistic and impact resistance of armored vehicles

Fig.34 Auxetic Materials used for various purposes and scales of applications
(a) Auxetic Foam for Snow-Sport Safety Devices [Allen et al, 2017]
(b) Petit Pli by Ryan Mario Yasin
(c) Diodon by Dynamorphe 2017
(d) [Gabriele Imbalzano 2015]

Design Concept

The design application focuses in the interface between the user and the impact moment of the fall. While I first conceptualized the application as a shock absorptive floor, the floor presented limits. Soft materials that absorb and dampen impact also create uneven surfaces that may cause tripping.[88] The application, therefore, was conceptualized as a protective apparel that prevents injuries from falls for seniors. The apparel is designed with a re-entrant honeycomb auxetic lattice that wraps around the body of the user, acting as an exterior structure. In Elipe and Lantada's comparative study of auxetic geometries such as the re-entrant honeycomb[89], double arrowed auxetic[90], chiral structures[91], rotating rigid/semi-rigid units[92], etc, the re-entrant and double arrowed auxetic structures showed the most effective young's modulus for energy absorption with the same mass compared to the other auxetic structures tested (Fig.35). The energy absorption occurs during plastic deformation when their hinge-like structure contracts proportionally around areas of pressure. By contracting upon impact, auxetic materials absorb shock by distributing force throughout the structure and densifying the material.[93] I therefore chose the re-entrant auxetic structure for Design Experiment 1 specifically for its high capacity for energy absorption and impact resistance.[94]

One of the main design goals of the apparel system is to provide a holistic system of protection without the need for individual articles and components like current protective wear available for seniors. The auxetic material was therefore parametrically designed to create a functional gradation of shock absorptive functionalities to create a continuous protective structure around the body. Functionally graded materials are materials that posses varied properties from one region of the material to another while remaining as a single material system.[95] Functionally graded materials allow for customized changes to the material to meet desired functionality at specific locations. In this specific application a functional gradation approach, the transition gradation of the auxetic material between protective and non-protective areas were explored. Then, the design of the overall assembly and system of the apparel was developed, incorporating the gradation system. To iteratively design and test various parameters of the gradation system, a digital parametric model was developed to precisely manipulate geometric variables of different iterations of design and prototypes (Fig.37). The prototypes were fabricated on the Formlabs 3 SLA printer, using the Formlabs elastic resin, chosen for its highest ability for elongation and tear strength amongst other available resins, to allow for repeated bending, stretching, and compressing of the material prototypes.[96]

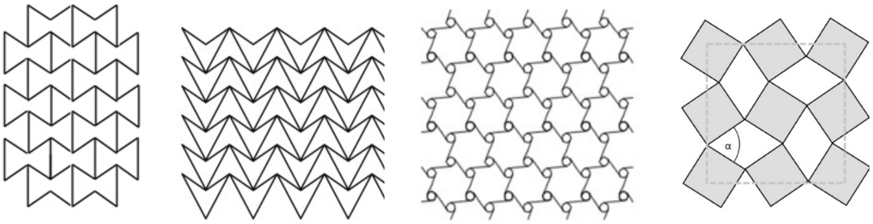
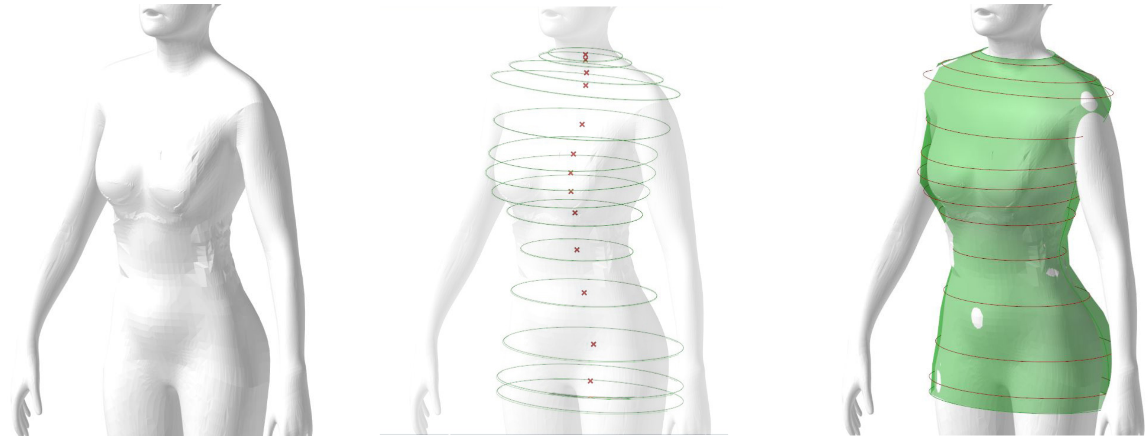


Fig.35 Left to Right: Re-entrant honeycomb, double arrowed auxetic, chiral structure, rotating rigid units

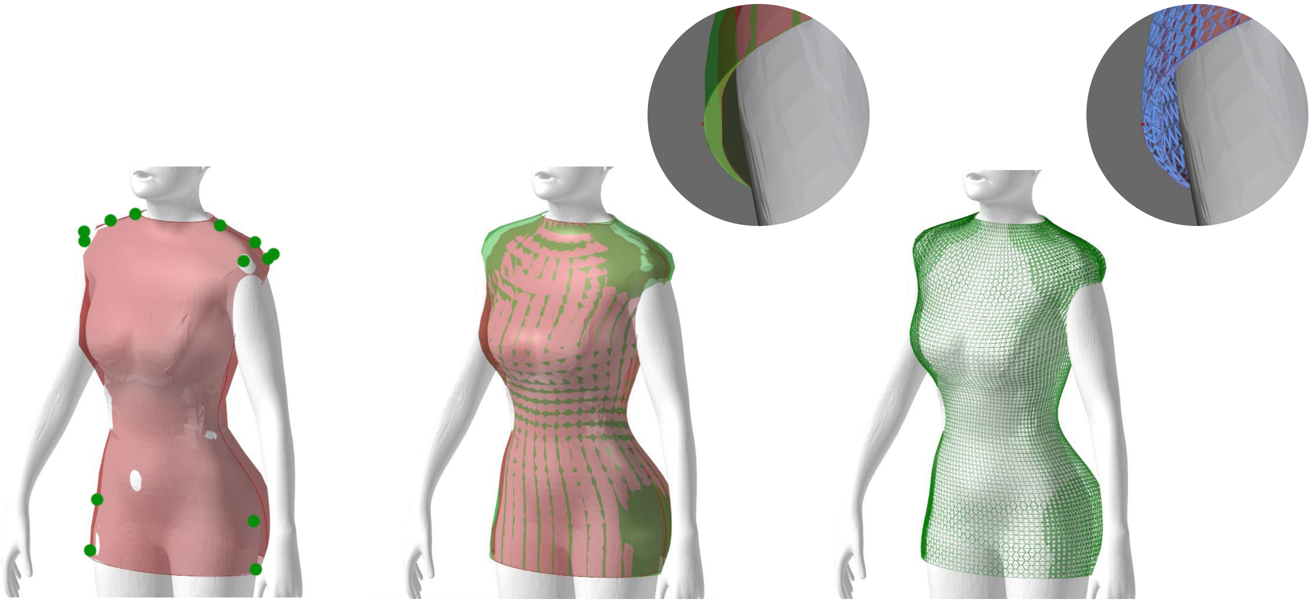
Fig.36 Top: Protective areas of the *Auxetic Apparel* Design



1. Body geometry is imported to digital design space

2. Points are generated for base form work of apparel

3. Mesh is made from body reference curves



4. Attractor points to densify the auxetic material are applied in reference to vulnerable points on the body

5. Second layer of mesh is offsetted creating thicker points

6. Auxetic Lattice is infilled between mesh layers

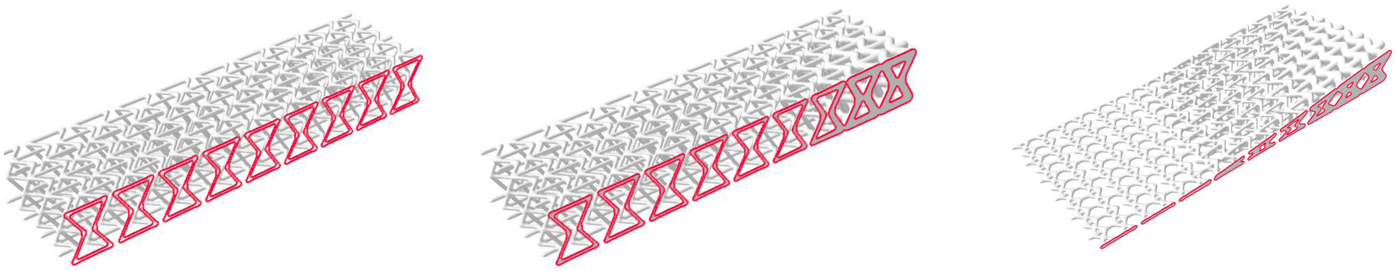
Fig.37 *Auxetic Apparel* Computational Design Process Diagram

Functional Gradation

The gradation was first hypothesized to be created only through changing the thickness of each member in the lattice system in order to vary degrees of shock absorptivity to maximize material efficiency as well as comfort. However, a print failure resulted in a deformation where the material had a gradient from a 3-dimensional to 2-dimensional profile, inspiring the addition of this gradation language to the transition design. (Fig.38) Going from a very volumetric lattice to a laminar lattice could be useful in form-fitting abilities because it has a lower flexural strength. The 2d elements allows for more flexible and thinner auxetic material around the parts of the body that do not require protection, maximizing material efficiency as well as formfitting abilities. The gradation consists of three parameters: surface area of gradient, individual lattice member thickness, as well as 3d to 2d formation of the lattice system. Together they can accommodate different needs of the body by parametrically varying the auxetic material, creating multiple transitions of shock absorption in the apparel. This gradient material structure optimizes structural performance, energy input in fabrication, and allows for an efficient material use.[97] The 2d elements of the gradation still presents challenges, as when printed perpendicular to the print bed resulted in deformations due to misalignment of print layers (Fig.41). Further alternative print orientation testing is therefore still required to fabricate larger surface areas of 2d elements.

Fig.38 Right: 3D-print failure resulting in 2D to 3D gradation effect

Fig.39 Bottom: Iteration diagram of auxetic material functional gradation design



auxetic lattice
with no gradation

auxetic lattice
member thickness gradation

auxetic lattice
member thickness &
2D- 3D gradation

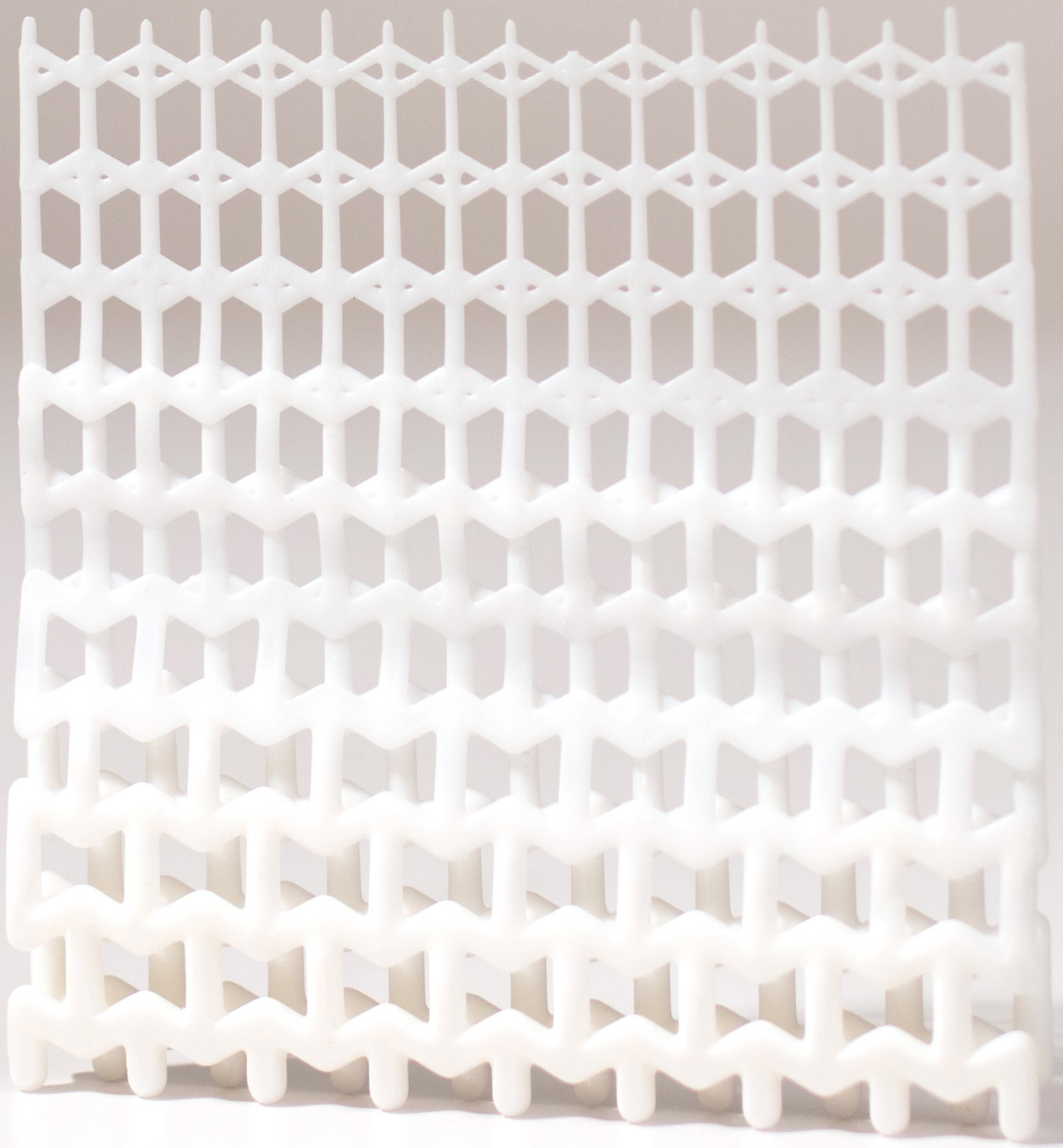


Fig.40 2D-3D Gradation Prototype 1

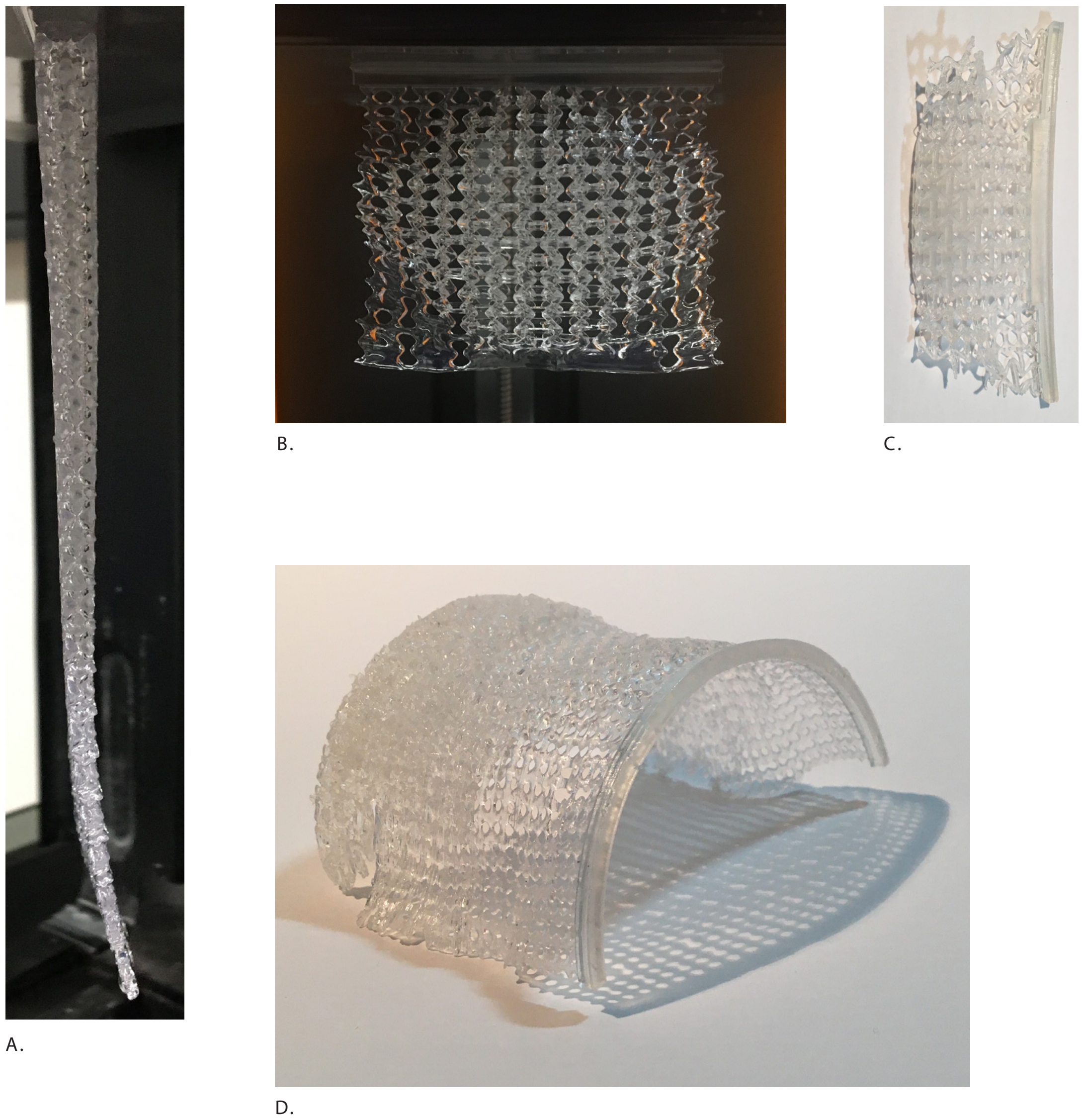
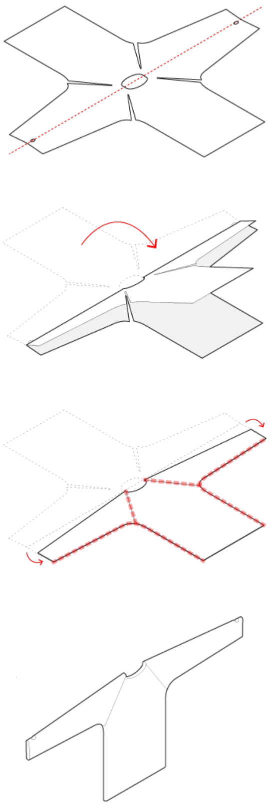


Fig.41 Functional Gradation Prototypes in elastic resin
(a) Linear 2D-3D Gradation
(b) Radial 2D-3D Gradation
(c) Half Radial 2D-3D Gradation
(d) Half Cylinder Prototype

Fig.42 Detail Image of Half Cylinder
2D-3D Gradation Prototype

Overall Assembly of apparel

The apparel was initially conceptualized as a single printed object which then through post processing of folding and adhesion will be shaped into the form of the apparel (Fig.43). However, due to failures of 2d elements, alternative methods of fabrication of 2d elements were explored where planar auxetic materials were made from 2-dimensional materials such as fabric (Fig.44). Assembly of the apparel was therefore revised for 3d elements of the apparel to be adhered through post processing on the 2d elements of the apparel (Fig.45). This method of fabricating 2d elements resulted in faster fabrication time, thinner material capabilities, and larger continuous surface area of the element, however, a comparative analysis of the two different models is required to determine the overall efficiency of this model.



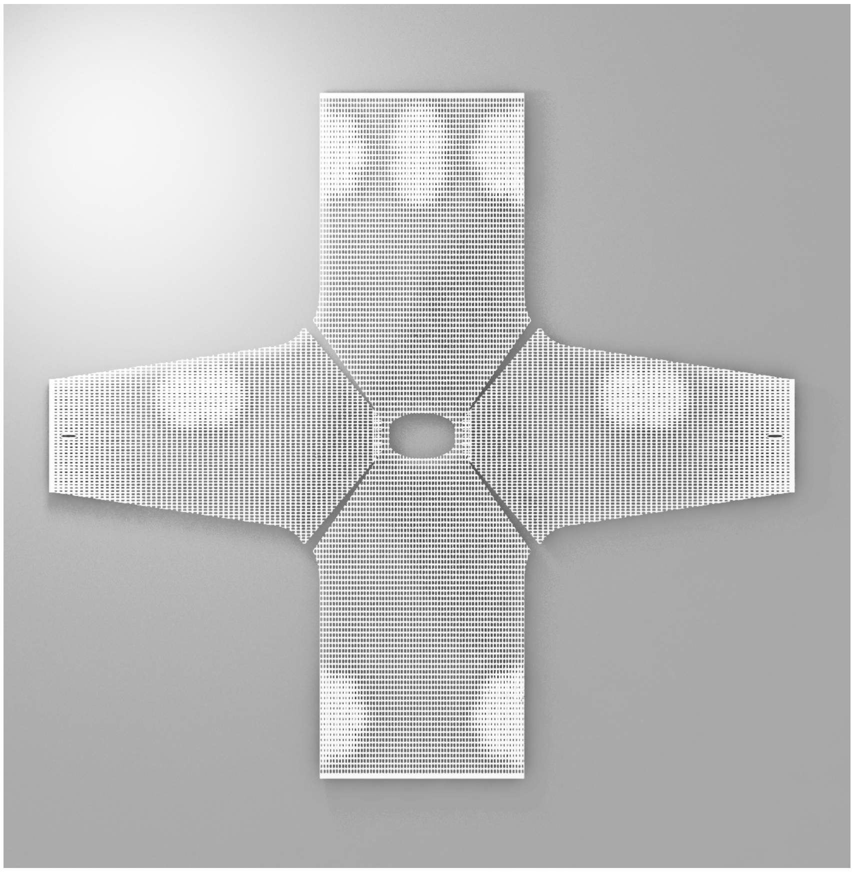


Fig.43   Top: Proposed Assembly of Overall *Auxetic Apparel* Shirt
Right: *Auxetic Apparel* Pattern Plan

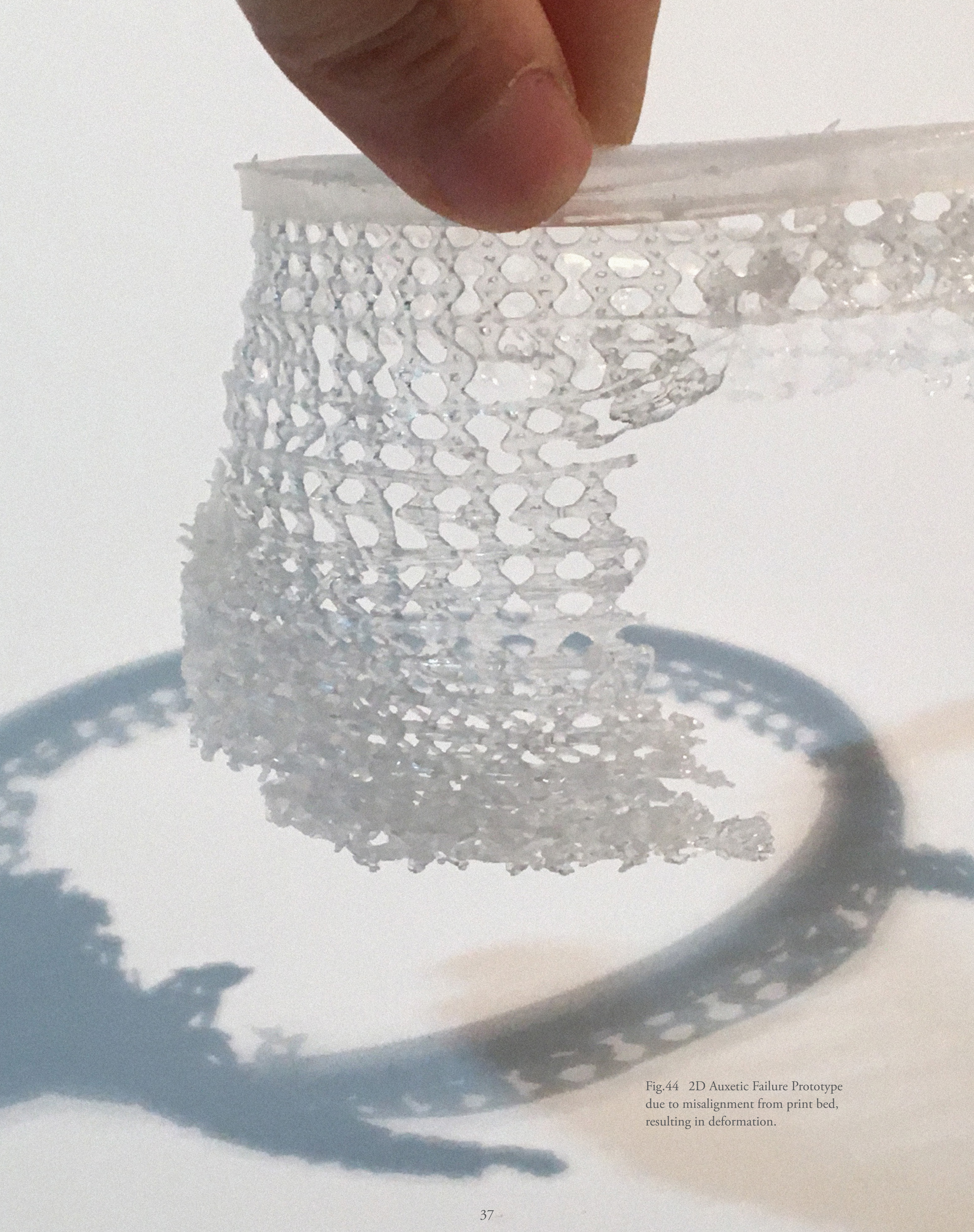
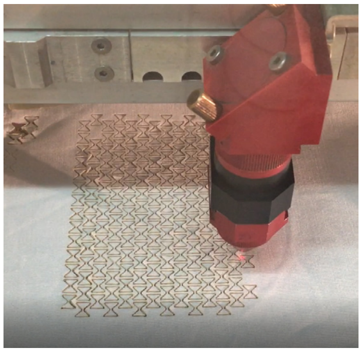


Fig.44 2D Auxetic Failure Prototype due to misalignment from print bed, resulting in deformation.



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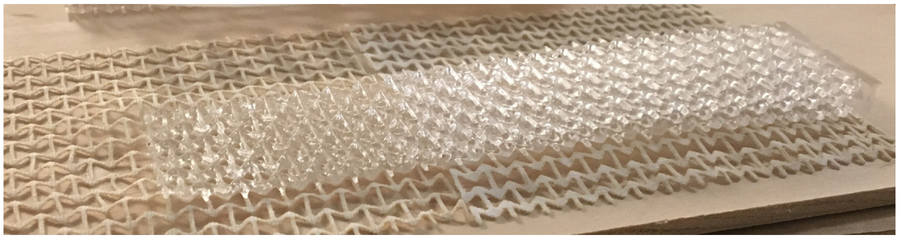

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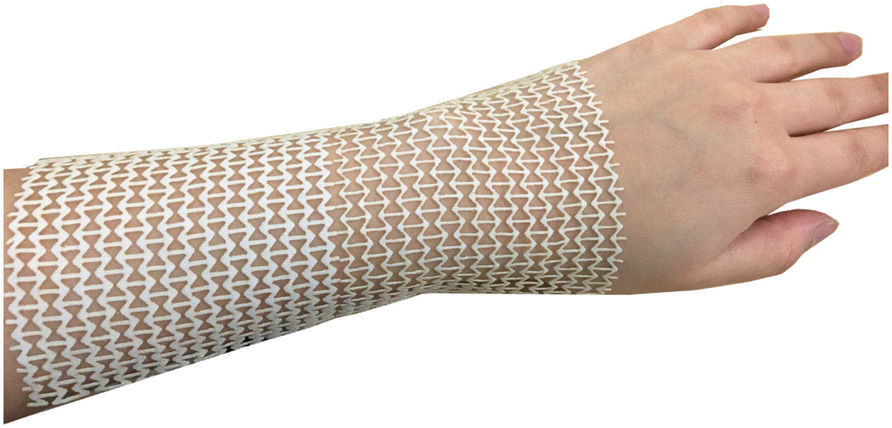


C.

Fig.45 2D Auxetic Fabric fabrication process
(a) Laser cutting process of 2D auxetic polyester fabric material
(b) 2D auxetic element adhered with 3D auxetic material to create gradation effect
(c) Fabric auxetic material draped on arm showcasing formfitting abilities

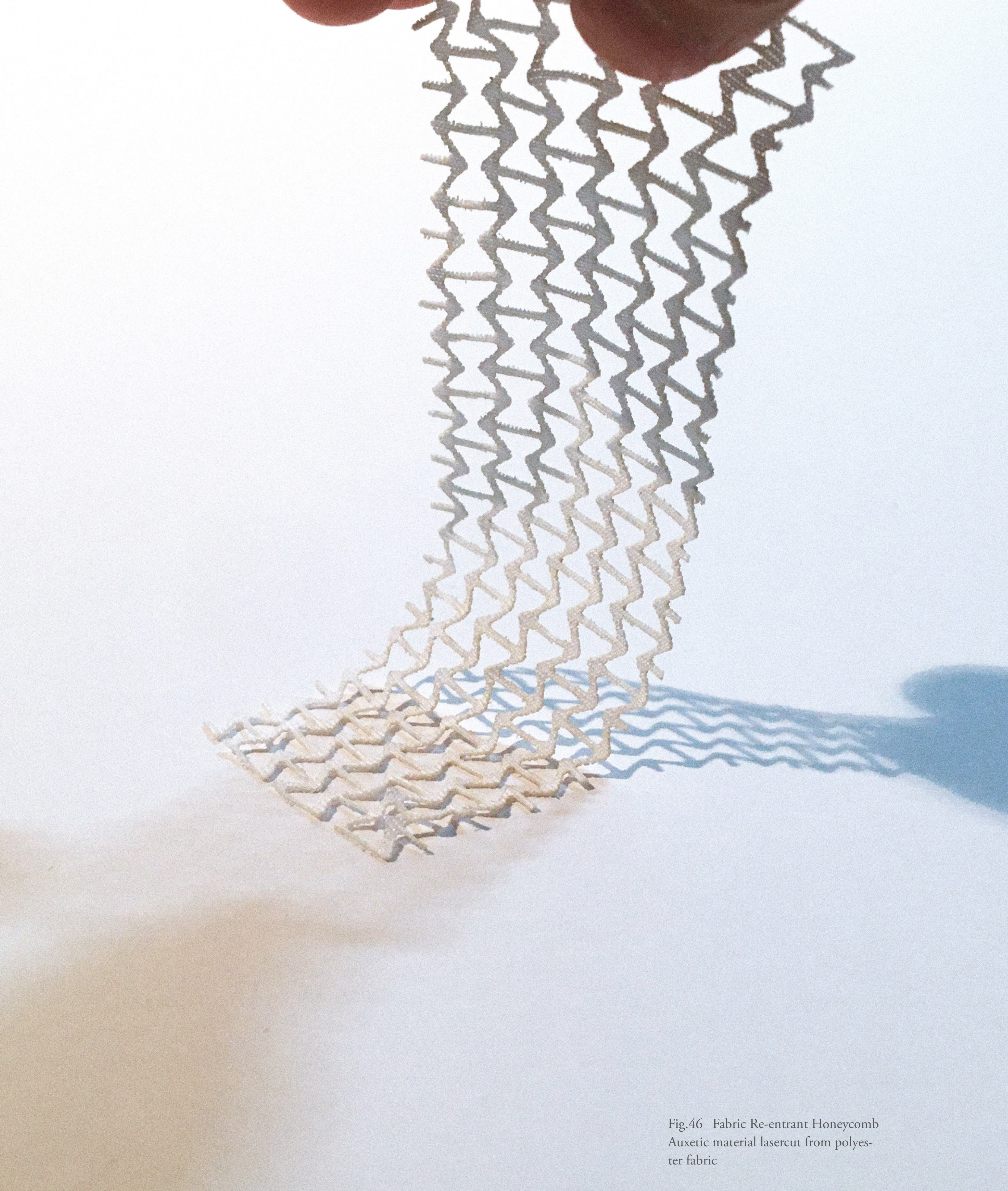
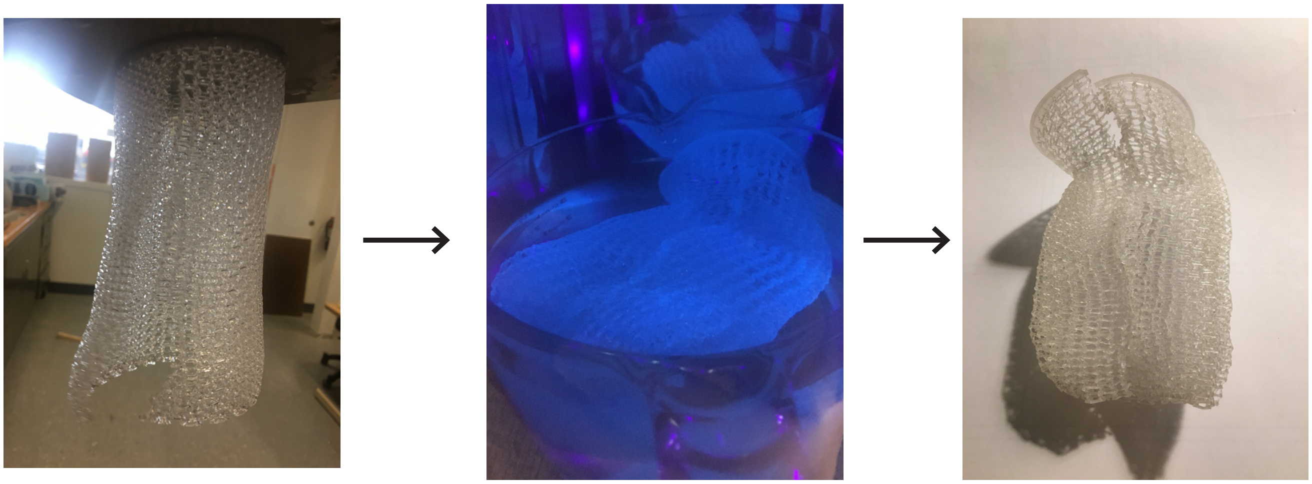


Fig.46 Fabric Re-entrant Honeycomb
Auxetic material lasercut from polyester fabric

Post Processing

In the curing process of Formlab's elastic resin, the auxetic lattice system revealed capabilities to retain a molded shape while remaining flexible after typical ultraviolet (UV) curing required of SLA prints (Fig.48). This ability presents an opportunity for post-process tailoring of the apparel design. While auxetic materials already obtain form-fitting abilities, post-tailoring allows for the users to further manipulate the apparel for their desired comfort and fit. The apparel then can be printed in standard forms, allowing customization and tailoring to come after fabrication and design (Fig .49). This eliminates the need for precise body measurements and custom digital modeling of the apparel prior to its fabrication, cutting the effort and cost of a customized manufacturing process that are often inefficient as extensive processes are required to transfer individual measurements into customized apparel patterns.[98]

Fig.47 Top: Ultra Violet (UV) curing process through UV Chamber
Bottom: UV flashlight used for pointed curing post-processes such as adhering seams



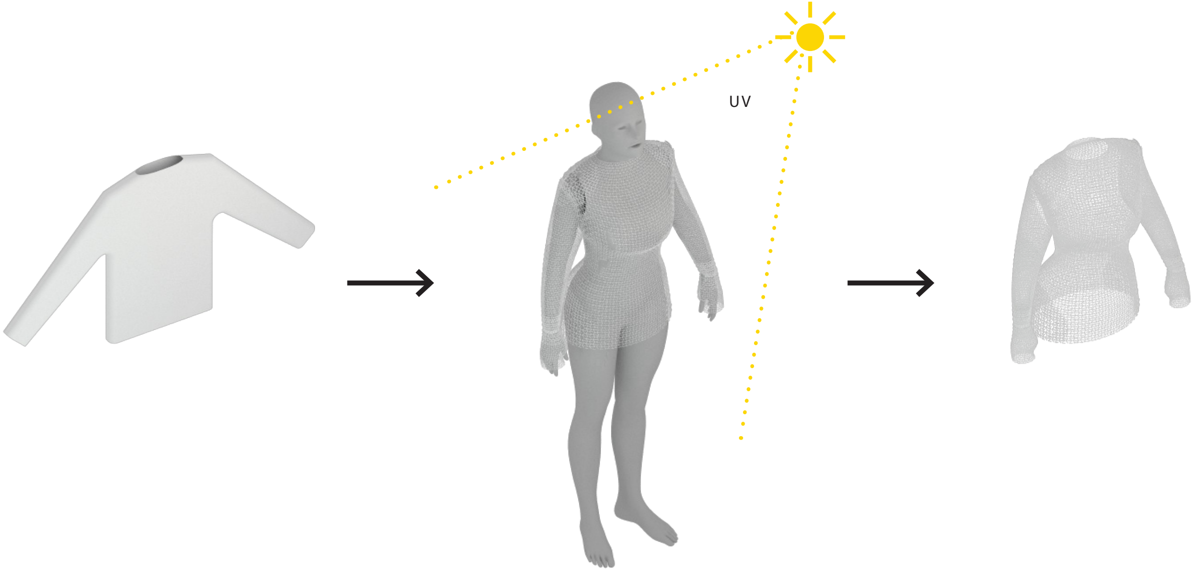


Fig.48 Auxetic material retained molded to the shape it was in during the UV curing.

Fig.49 Diagram of utilizing shape-retention behavior for potential UV post-tailoring process for *Auxetic Apparel*

Discussion/Outlook:

Although the auxetic protective suit design went through extensive exploration and iterative design, the prototyping failures were the source of the most significant improvements. In further development, the print failure that resulted in a 3D to 2D gradient can be explored further to self generate the thickness gradient by manipulating the material detachment to the bed. While more experiments are required to test its effectiveness, this integration allows for autonomous gradation in the material that eliminates the need to digitally model the change in form, speeding up the process of design and digital modeling.

The material of the suit could also be explored to further improve the post-tailoring process. If the apparel was made of materials that possess reversible shape retention abilities such as shape memory polymers, the tailoring of the apparel could be reversible, allowing the apparel to be repeatedly reshaped to fit the body over time. This presents great benefits as the apparel can then adapt to the physical changes of the body as we age, also creating a sustainable alternative for apparels.

The auxetic geometry pattern used in the material of the apparel can be further explored to compare shock absorption abilities as well as user comfort. Different auxetic patterns can be tested and researched for different functions required for the body such as expansion, flexibility, porosity, weight, surface quality, and used to create another functional dimension to the gradation of the material. Additional components of the apparel can also be developed further using the same material language to add more features such as protection for the head through a hood system.

Both 2D and 3D re-entrant honeycomb auxetic systems have been widely crush tested, indicating their good ability of energy absorption.[99]Further shock and impact testing is required, however, to evaluate the energy absorptive performance of the *Auxetic Apparel* as the auxetic system created consists of different materials than tests previously conducted by other researchers. Additionally, further testing of shock and impact response specific to falling impacts and scenarios are required. Current prototyping consists of small-scale sections of the apparel, scopes beyond the thesis, such as fabrication and development of the entire suit, are planned to be explored further external to the thesis at the Autodesk Residency program.

Fig.50 Detail render image of *Auxetic Apparel* Arm

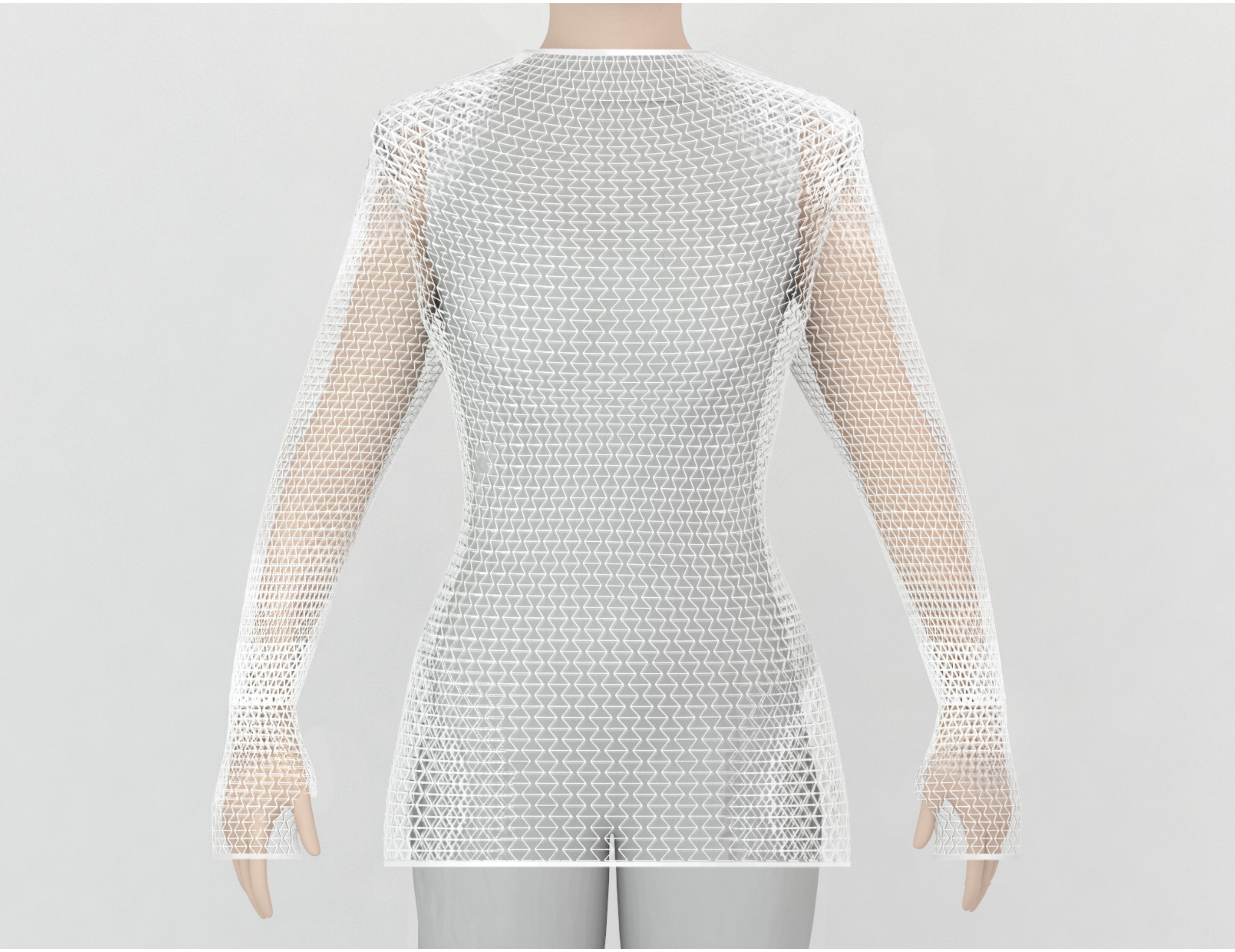


Fig.51 Elevation of *Auxetic Apparel*
Left: Front Elevation
Right: Back Elevation

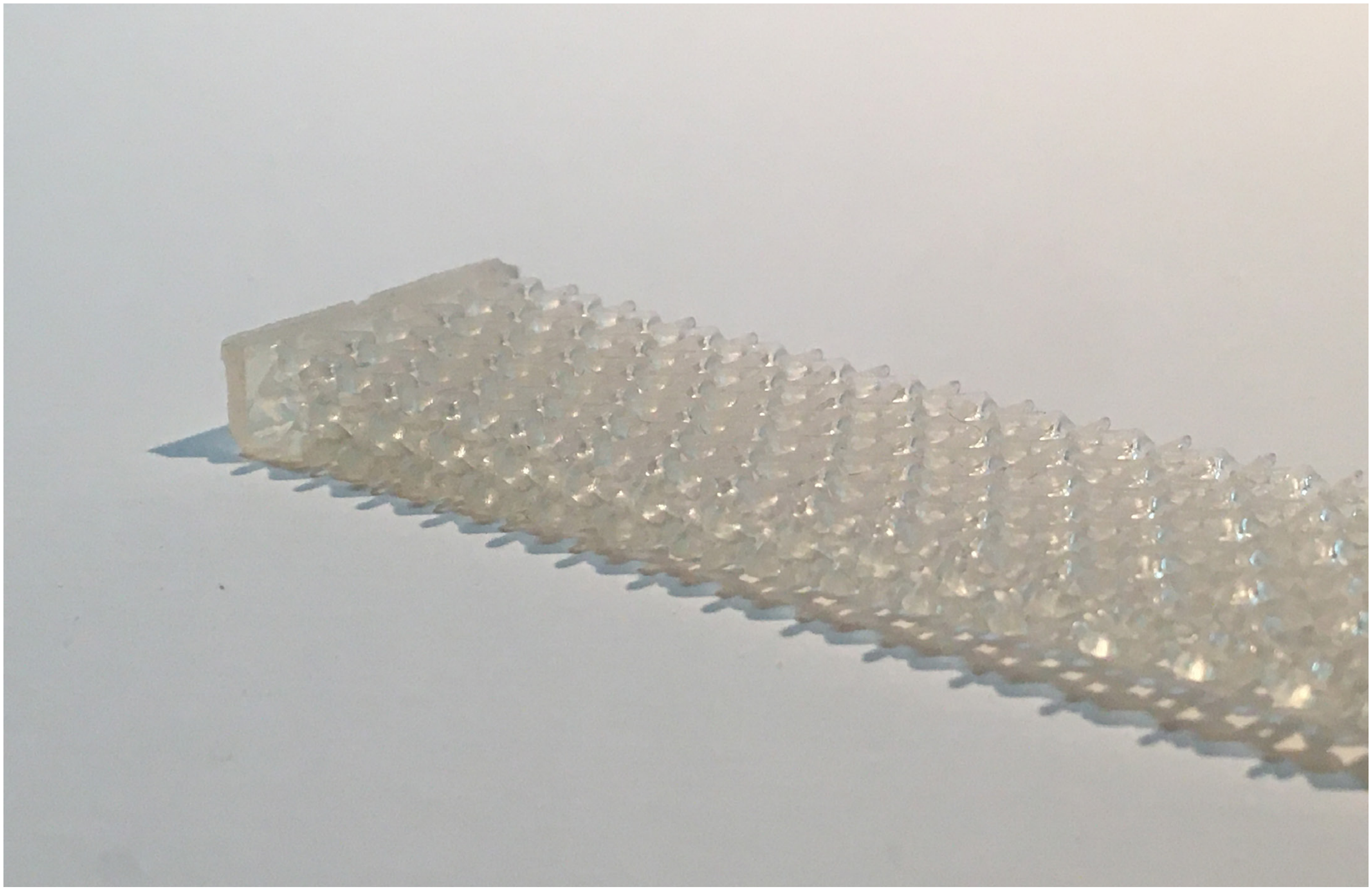
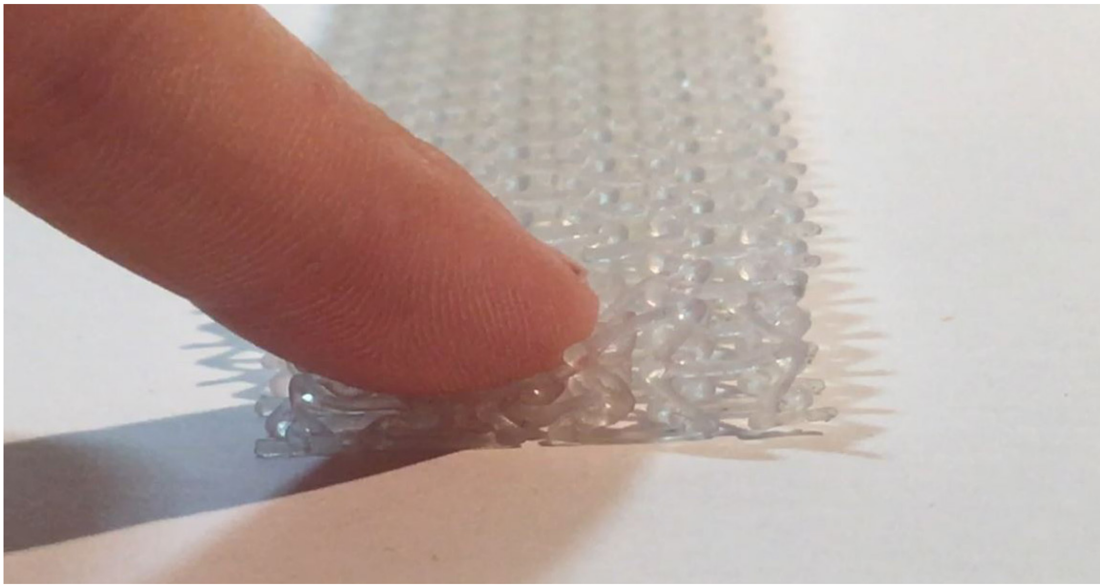
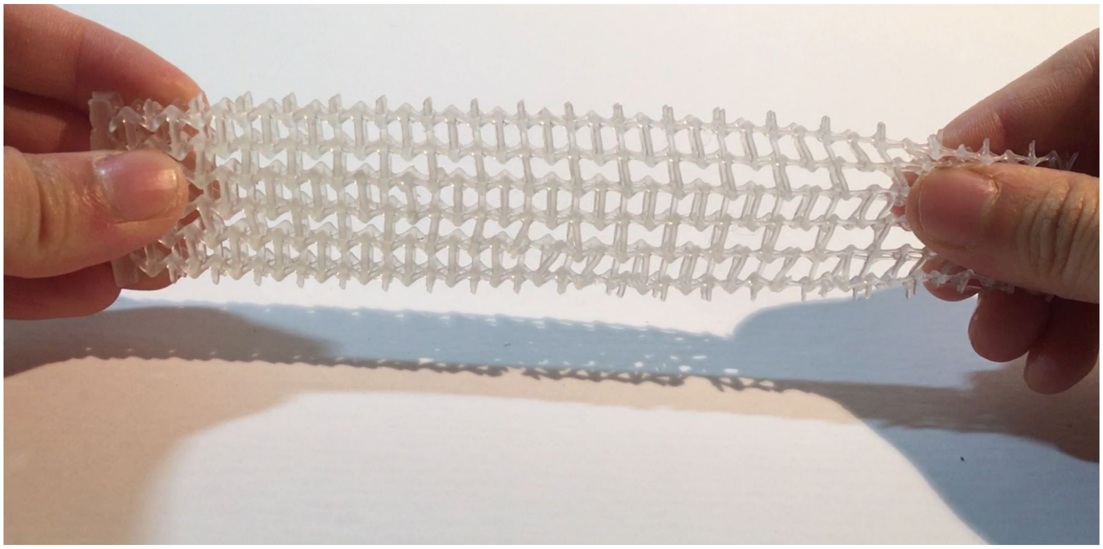


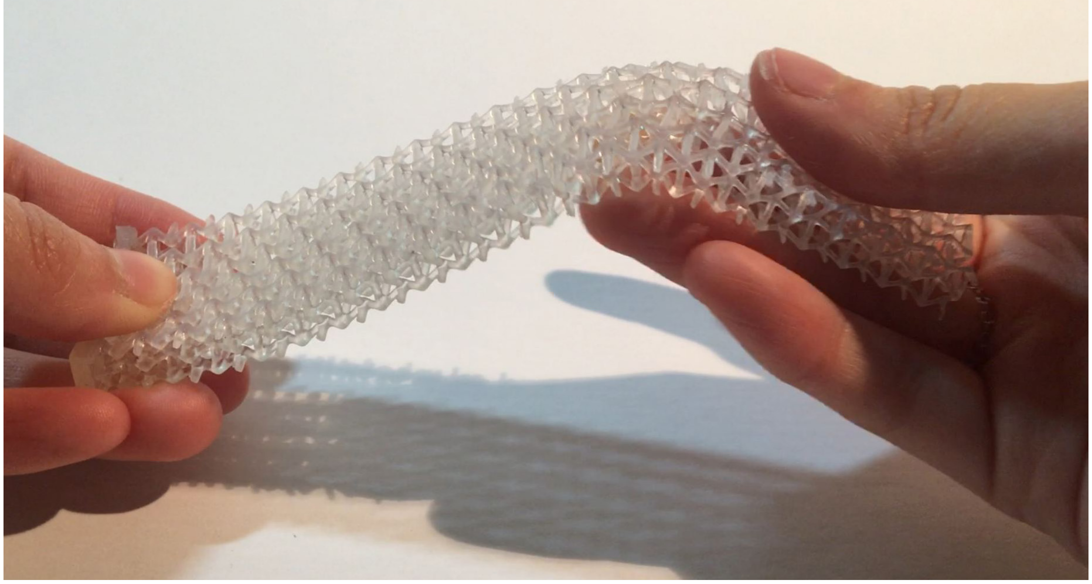
Fig.52 Left: Auxetic Apparel Material Prototype
Right: Detail render image of *Auxetic Apparel* showing elbow,wrist, and hip elements



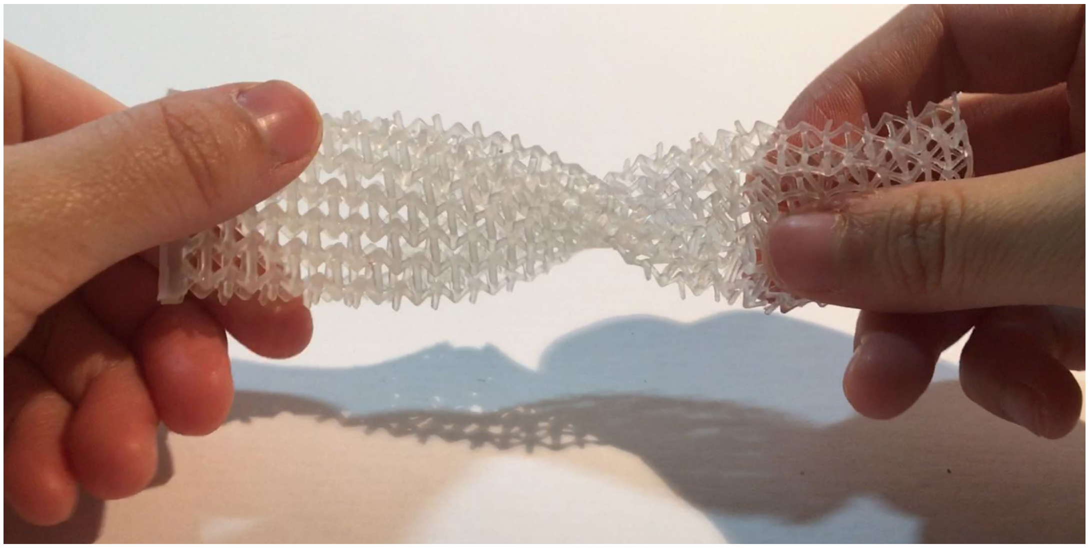
Compression



Stretch

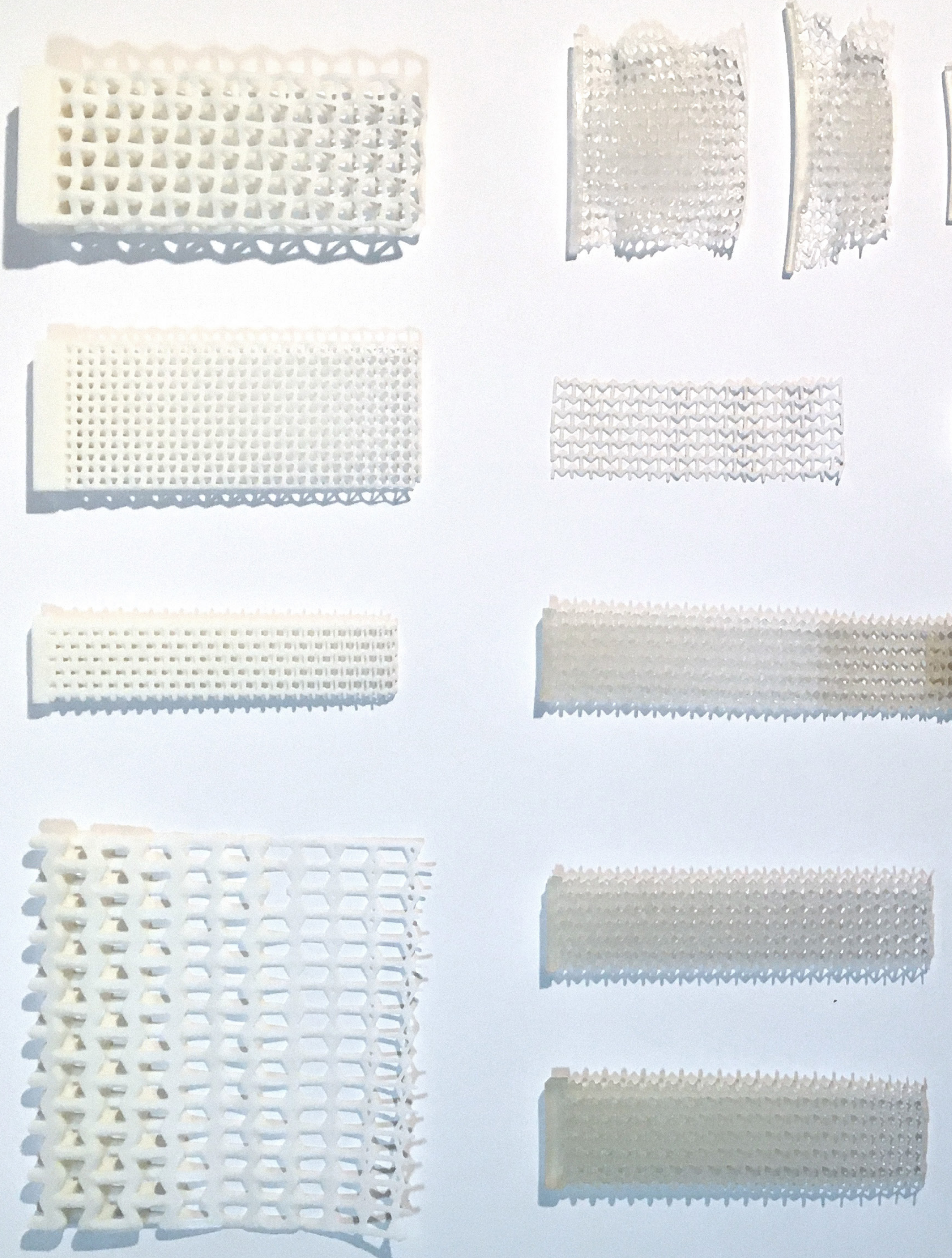


Curvature



Twist

Fig.53 Demonstration of range of motion of *Auxetic Apparel* material



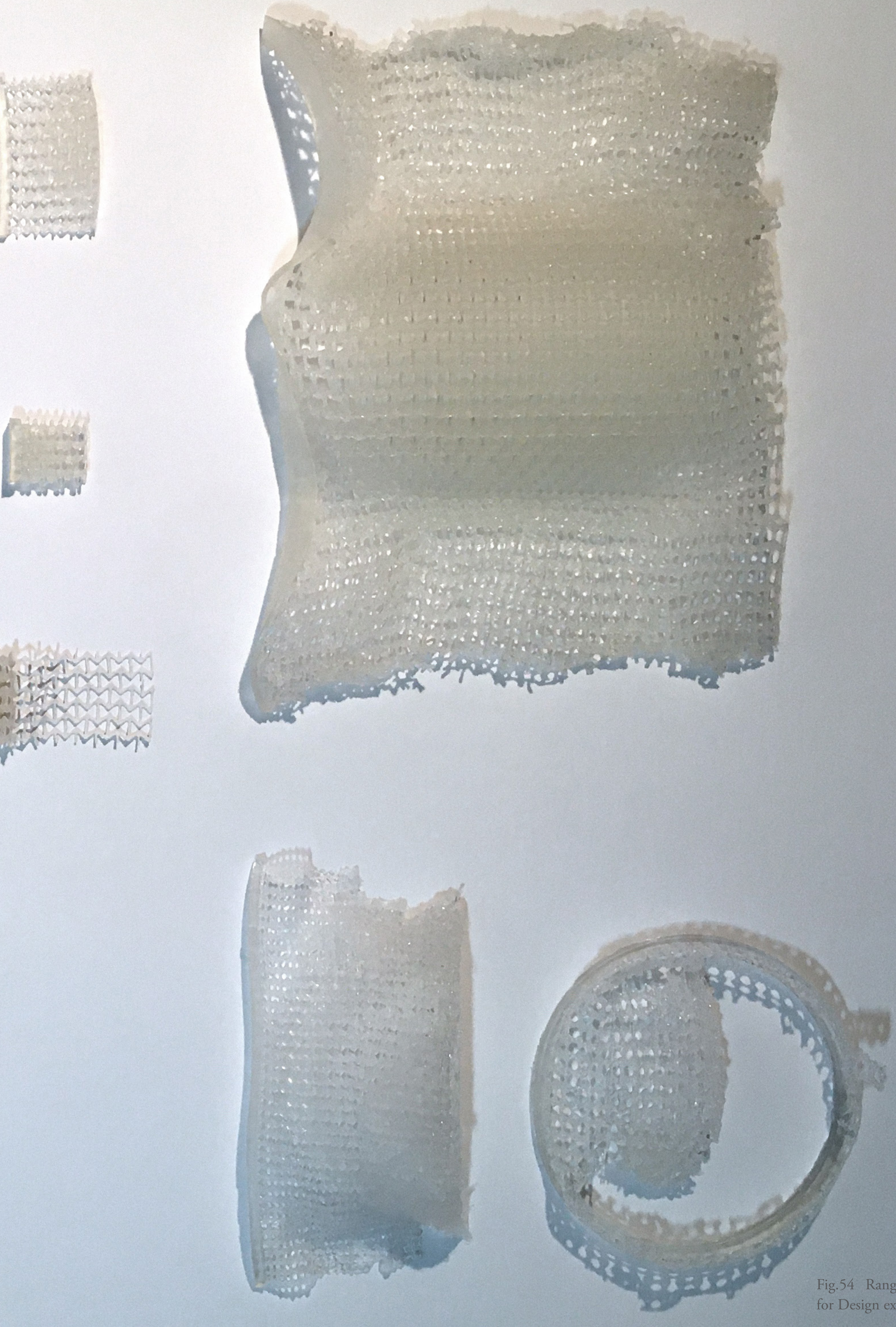


Fig.54 Range of prototypes explored for Design experiment 1

Fig.55
Top: Water bead on hydrophobic materials can move freely on its surface.
Bottom: Color contrast of water to surface material is often hard to detect for seniors with reduced vision.

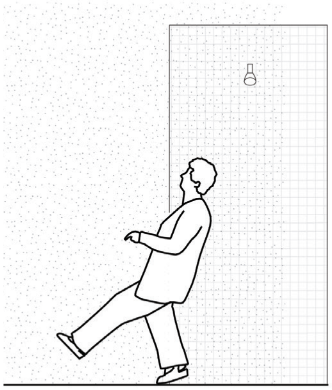
Design Experiment 2:

Hydro Floor

Anatomy of Slipping

While everyone slips on wet surfaces from time to time, as we age, changes in our bodies make us more prone to slipping.[100] First, our sight deteriorates, making it harder to see lower contrasting objects such as water on surfaces, making it harder to avoid them.[101] Second, our ability to react and regain balance is delayed with age, making it harder to prevent falls by rebalancing.[102]

Slipping usually occurs in wet areas of our homes such as the bathroom or kitchen, especially because we tend to use low friction materials that are often hydrophobic for the floors in these areas.[103] This property lowers the friction level because water particles can freely slide across without bonding to the surface of the material, causing us to slip more easily.[104] Prior study of anti slip mats showed that raised textures such as ridge and bumps were used increase grip and to prevent slipping. These are valuable observations that have informed designing gripping mechanism for the design exploration.



Smart material Application: Wood & Hydro-chromic Paint

When we are in water, most of us will find that our fingers and toes develop wrinkles. Studies show that this change is a functional one, where the wrinkles improve grip in water by increasing surface area through creating ridges on the surface of the skin, therefore increasing the friction between our skin and the surface of the object (Fig.56).[105] Mimicking this phenomenon, I designed a holistic water sensitive floor system to mitigate slipping. When the floor system is wet, it reacts by extending rectangular ridges to increase grip and changes color for water detection. When the floor is dry again, it returns to its original state and lays flat (Fig.58). Wood is a material well known for its hygroscopic nature of shrinking and expanding.[106] This unique property was utilized to generate the moving ridges by allowing them to expand with water, protruding the surface to create ridge forms. Hydro-chromic paint, a pigment that changes from opaque to transparent once in contact with water was used to change the appearance of the surface to alert of the presence of water.

Design Concept:

Two main components make up the floor system design: color signal and friction. The colour signal was created by using hydro-chromic paint on the surface of the tile to alerts the user of potential slipping. Wood expansion joints were utilized to create dynamic friction points on the floor that maximize friction.

The developed system uses parametric density gradient of friction points on the floor which in turn allows for varying degrees of grip in different wet environments. Various friction controlling parameters can be altered in the design such as ridge height, ridge width, and ridge spacing (Fig.57). Varying these parameters creates varying friction levels, allowing for design to accommodate different needs within the environment such as higher friction in wetter zones and lower in entries to wet zones.[107]

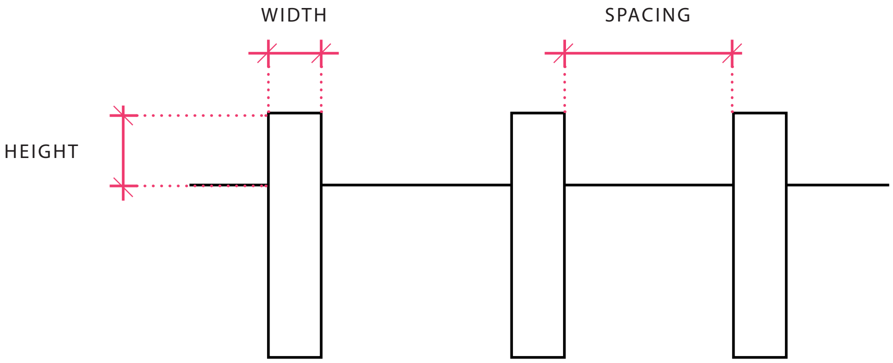


Fig.56 Top: Finger skin forming wrinkles under water for enhanced grip [Oi Ying Wong]

Fig.57 Bottom: *Hydrofloor* Ridge Parameter Diagram

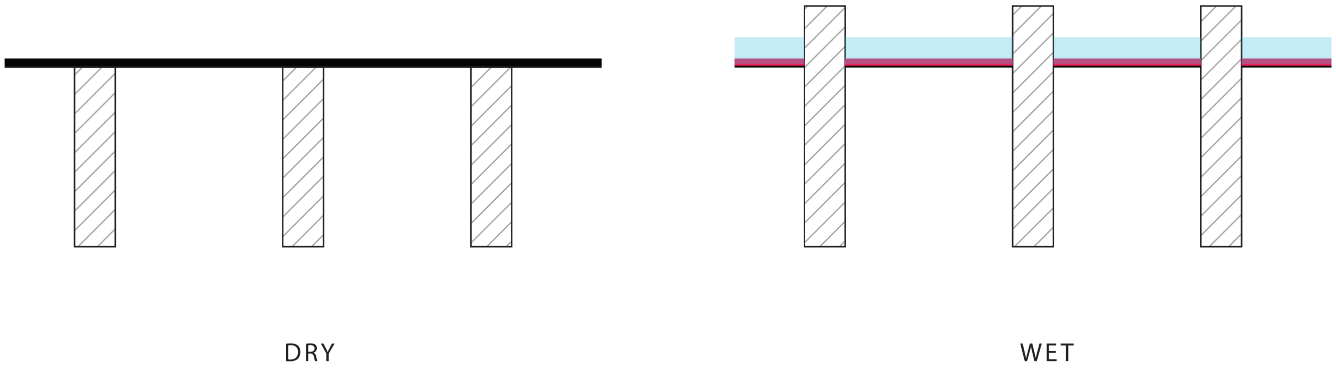


Fig.58 Dry vs Wet Behaviors of *Hydrofloor* concept diagram

* Wood moisture expansion does not move equally in all directions. Direction of wood grain within the piece of wood will determine which dimension will increase the most. The grain tangent to the growth of wood rings is known to expand and contract the most and was used as the direction of growth for ridges of the *Hydrofloor*.[106]

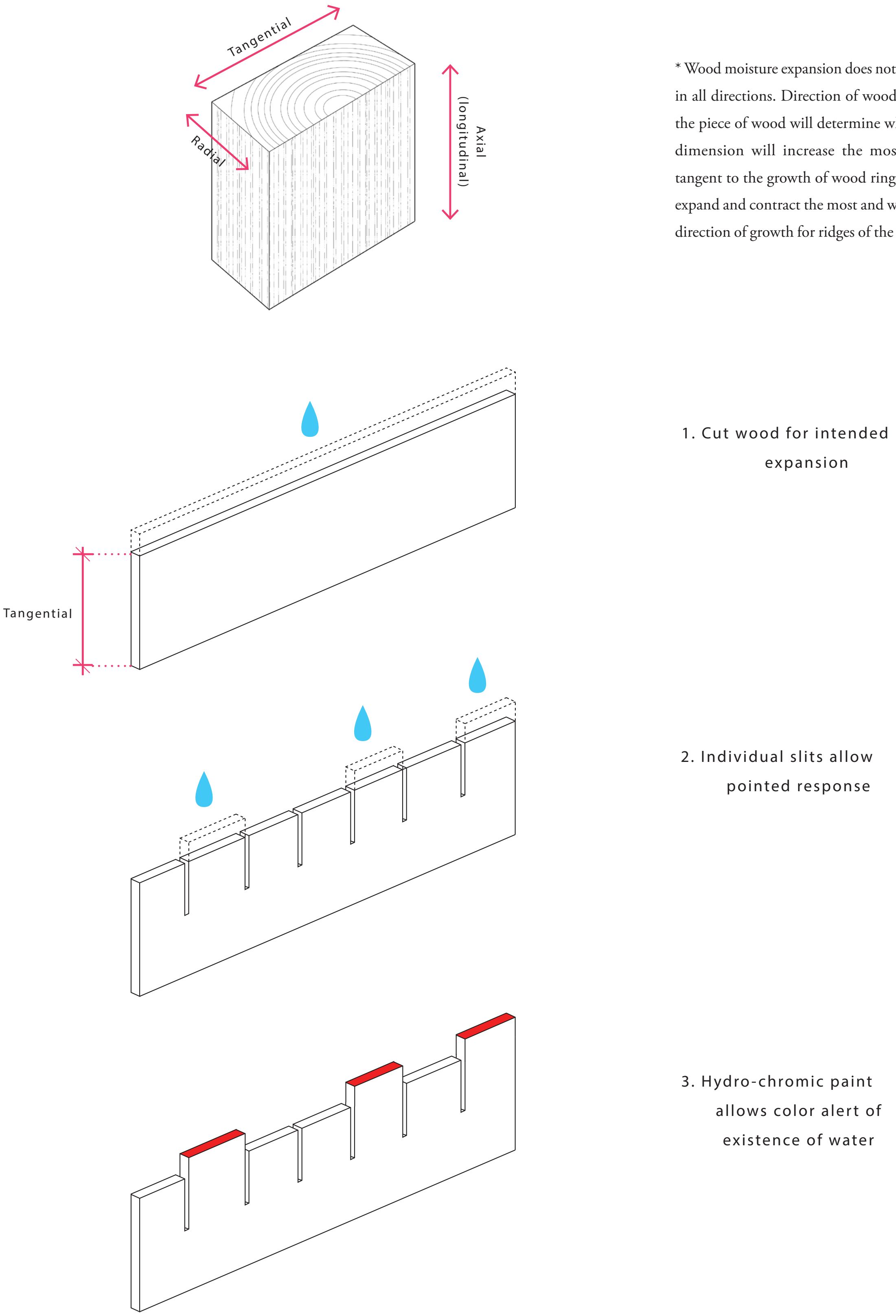


Fig.59 *HydroFloor* ridge cut diagram

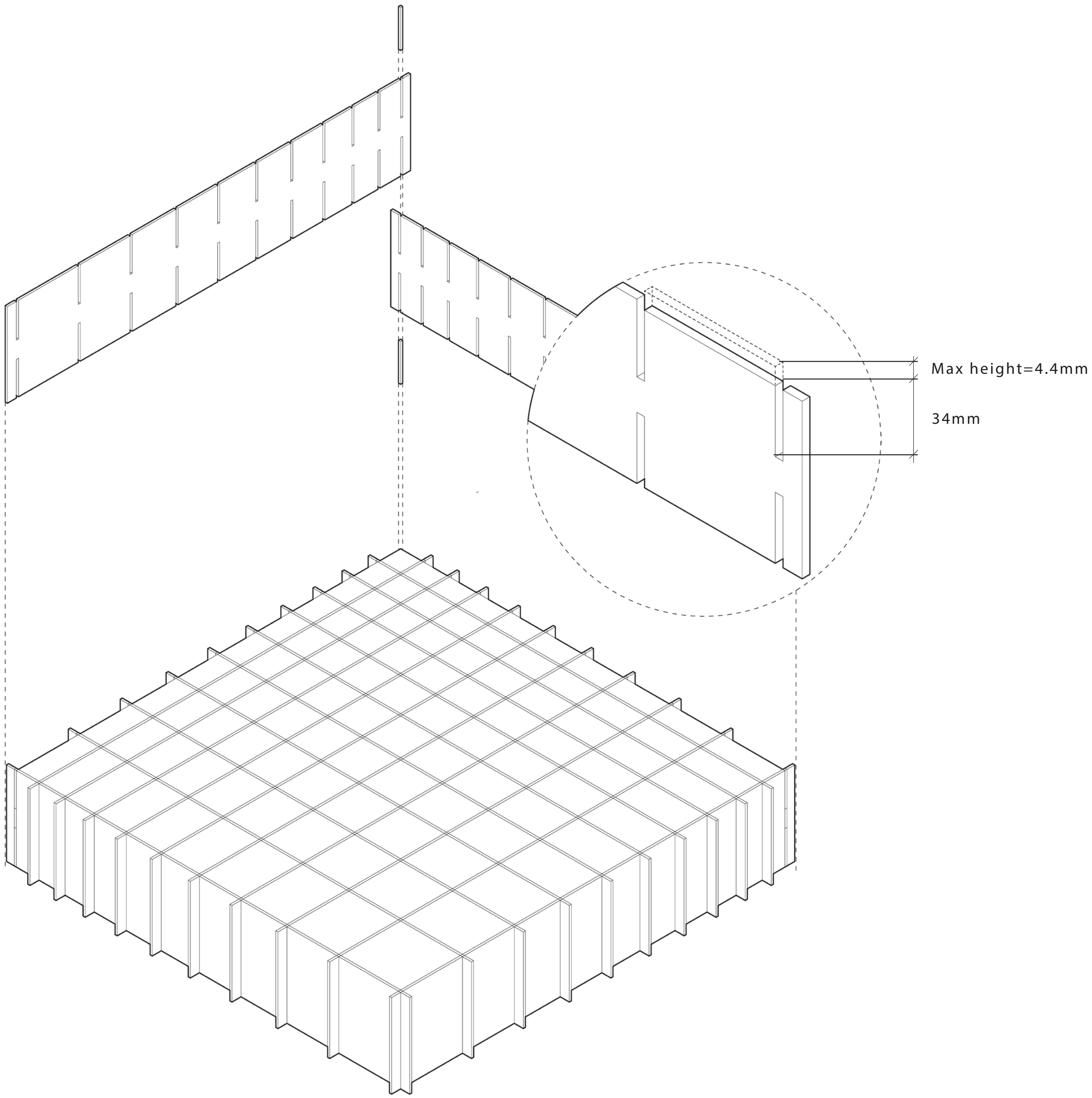


Fig.60 *Hydrofloor* Assembly Diagram

Friction Levels

The prototype has a height change variation of the wood ridges from 33mm to 37mm, creating 4mm tall protrusions in the floor system (Fig.61). Research shows that beyond 1mm in height, ridges give a significant increase in friction, minimizing chances of slipping compared to its original flat state.[108] Some challenges still exist, however, in the response time of the wood ridges to water in reaching their maximum height.

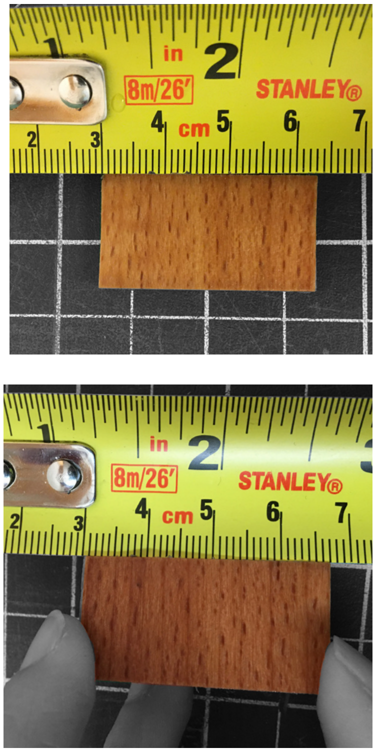


Fig.61 Wood Dry vs Wet Dimension
Top: Dry state measuring 33 mm
Bottom: Wet state measuring 37mm

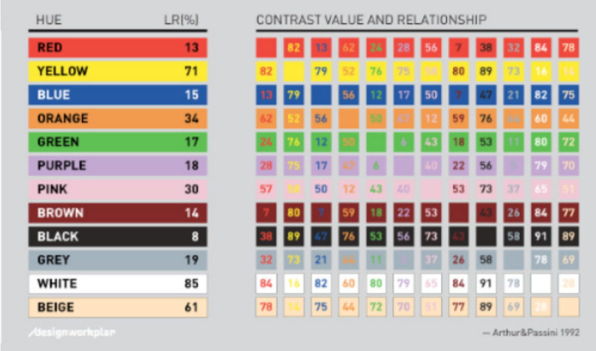
Color Change

With age, our ability to detect colors and contrast significantly decreases.[109] To accommodate this change in ability and ensure the highest chance of water detection, the tiles are made of colors with red hues rather than blue or yellow colors that are harder to see with age.[110] The contrast of the colors used for the floor system was calculated using Arthur & Passini's contrast difference equation described in their book Wayfinding from 1992, which reliably determines the legibility of signs in architectural contexts.(Fig.62)[111] The formula is based on the light reflectancy (LR) readings in percentages for each color, and provides the contrast level between two colors to each other. The colors used for the prototype have a contrast value of 85%, surpassing the ADA requirements of contrast value of 70%, thus assuring legibility for most.[112] The response time of the color change is immediate and becoming more apparent with time and water saturation (Fig.64).

Arthur & Passini's Contrast difference equation:

$$\frac{\{K1-K2\}}{K1} \times 100 = H \qquad \frac{\{85-13\}}{13} \times 100 = 84.7$$

K1= Highest color Value K2= lowest color value H= contrast value



HUE	LR(%)	CONTRAST VALUE AND RELATIONSHIP											
RED	13		82	13	62	24	28	56	7	38	32	84	78
YELLOW	71	82		79	52	76	75	58	80	89	73	16	14
BLUE	15	13	79		56	12	17	50	7	47	21	82	75
ORANGE	34	62	52	56		50	47	12	59	76	44	60	44
GREEN	17	24	76	12	50		6	43	18	53	11	80	72
PURPLE	18	28	75	17	47	6		40	22	56	5	79	70
PINK	30	57	58	50	12	43	40		53	73	37	65	51
BROWN	14	7	80	7	59	18	22	53		43	26	84	77
BLACK	8	38	89	47	76	53	56	73	43		58	91	89
GREY	19	32	73	21	44	11	5	37	26	58		78	69
WHITE	85	84	16	82	60	80	79	65	84	91	78		28
BEIGE	61	78	14	75	44	72	70	51	77	89	69	28	

/designworkplan

— Arthur&Passini 1992

Fig.62 Contrast Equation & chart for ADA compliant color contrast from book *Wayfinding: People, Signs, and Architecture* by Paul Arthur & Romedi Passini, 1992

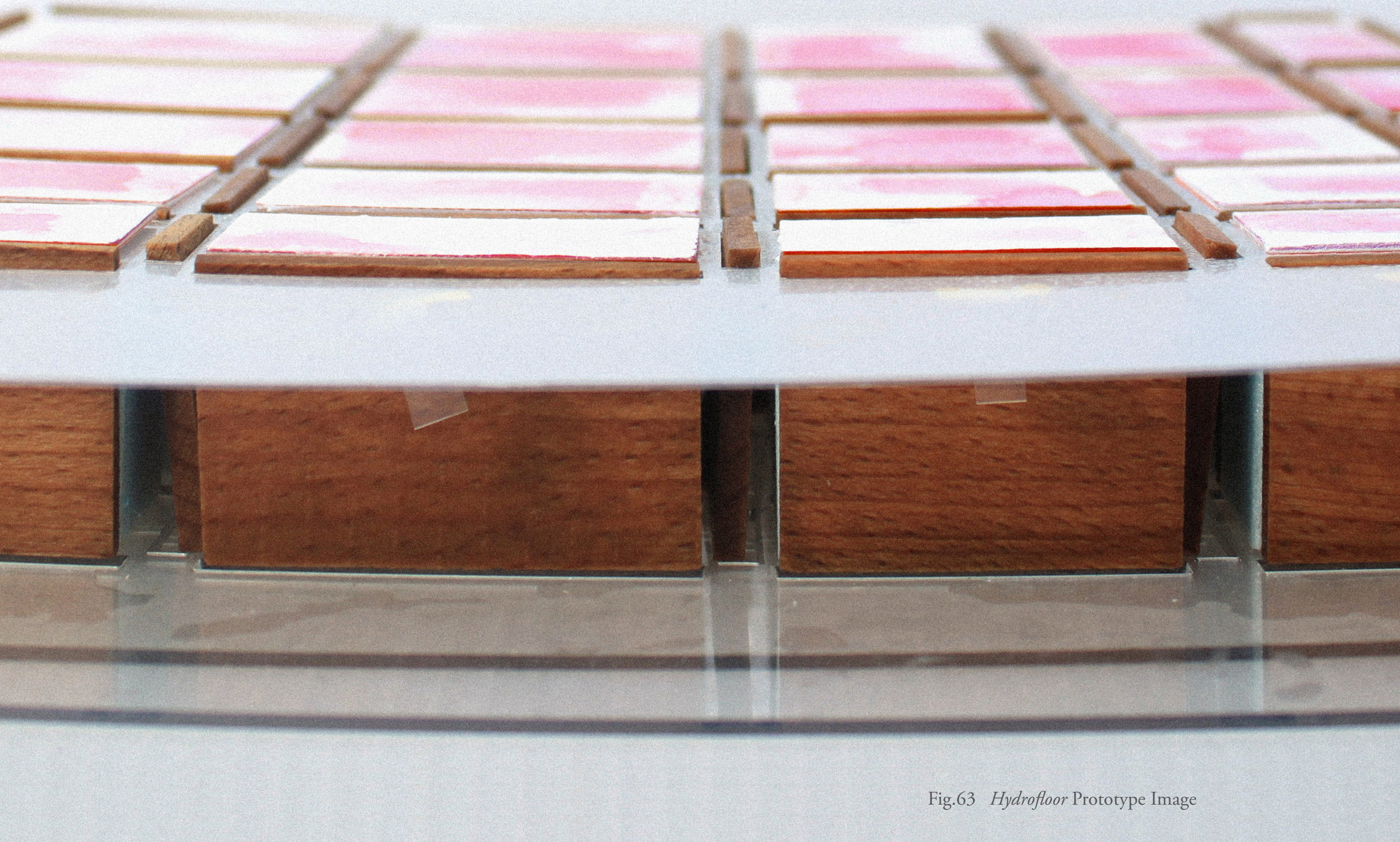


Fig.63 *Hydrofloor* Prototype Image

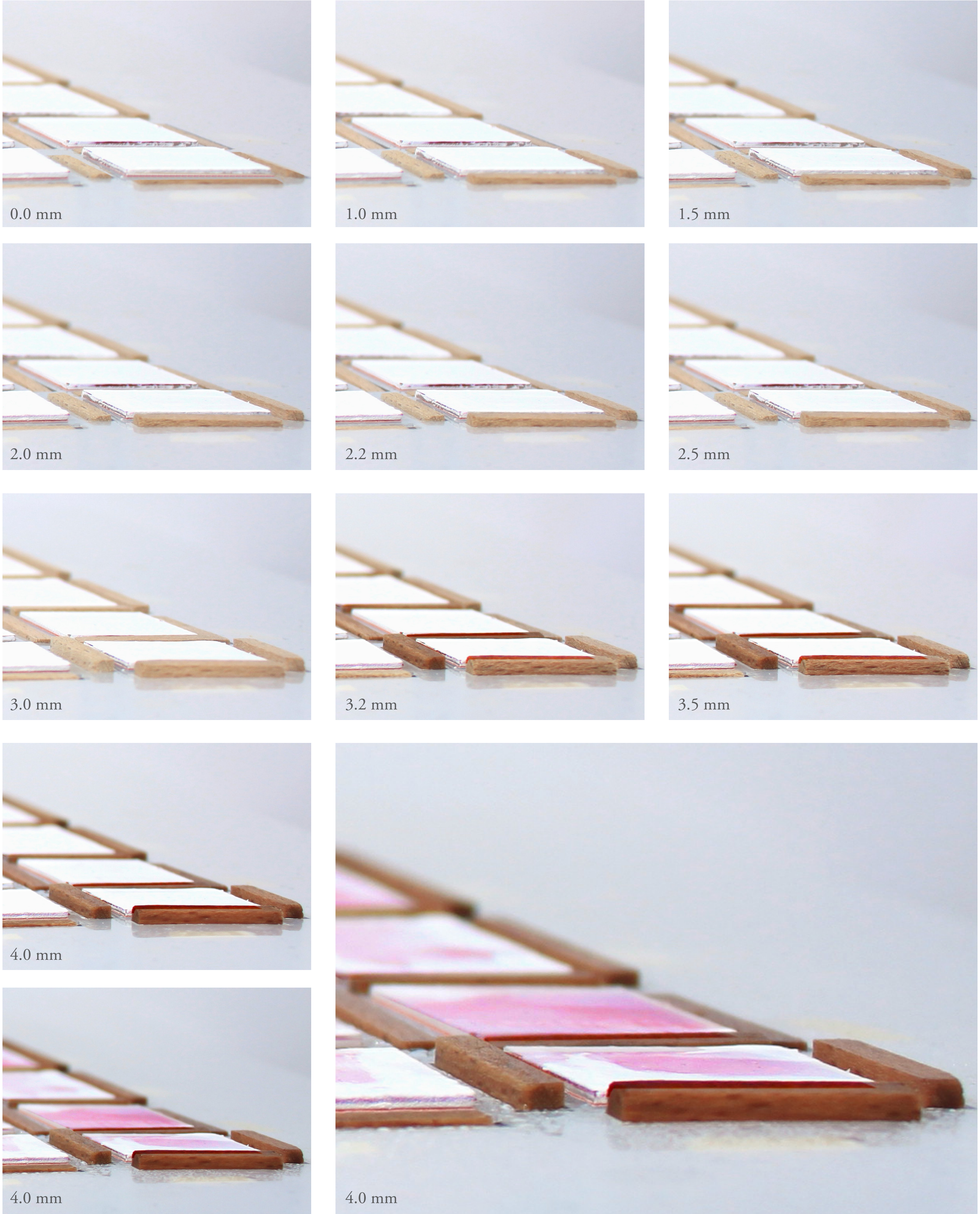


Fig.64 *Hydrofloor* time lapse photo series showing increase in ridge height & color transition in response to water

Fig.65 Different thickness/layers of hydro-chromic paint showed to dry at various rates resulting in inconsistent color change

Discussion/Outlook:

While the prototype proves the concept of the floor system, further optimizations can improve the design's efficiency and effectiveness. For instance, the response time of the wood joints could be reduced through slit cuts that allow it to absorb water faster and with it quicken the expansion. Additionally, these slit cuts could be in patterns, like the kirigami patterns, that augment the amplitude of the wood's expansion (Fig.66). Other materials that possesses hydrophilic expanding behaviors could also be considered and be tested for response time and rate of expansion in substitution for wood. While further research and design is required to fully develop a floor system that will holistically integrate with standard architectural floor structures, potential applications include interior and exterior use, providing anti-slip floors for all (Fig.69).

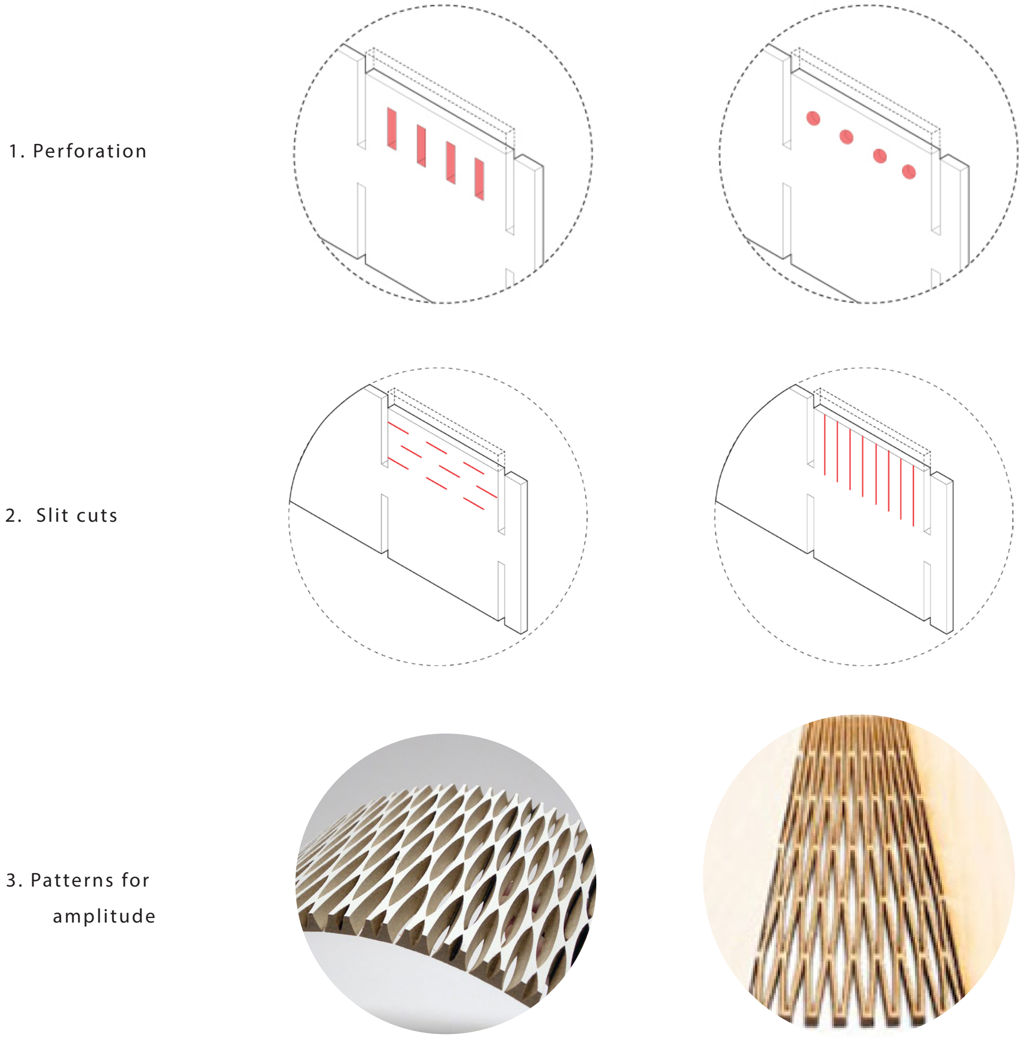


Fig.66 Potential future response optimization tests to reduce response time

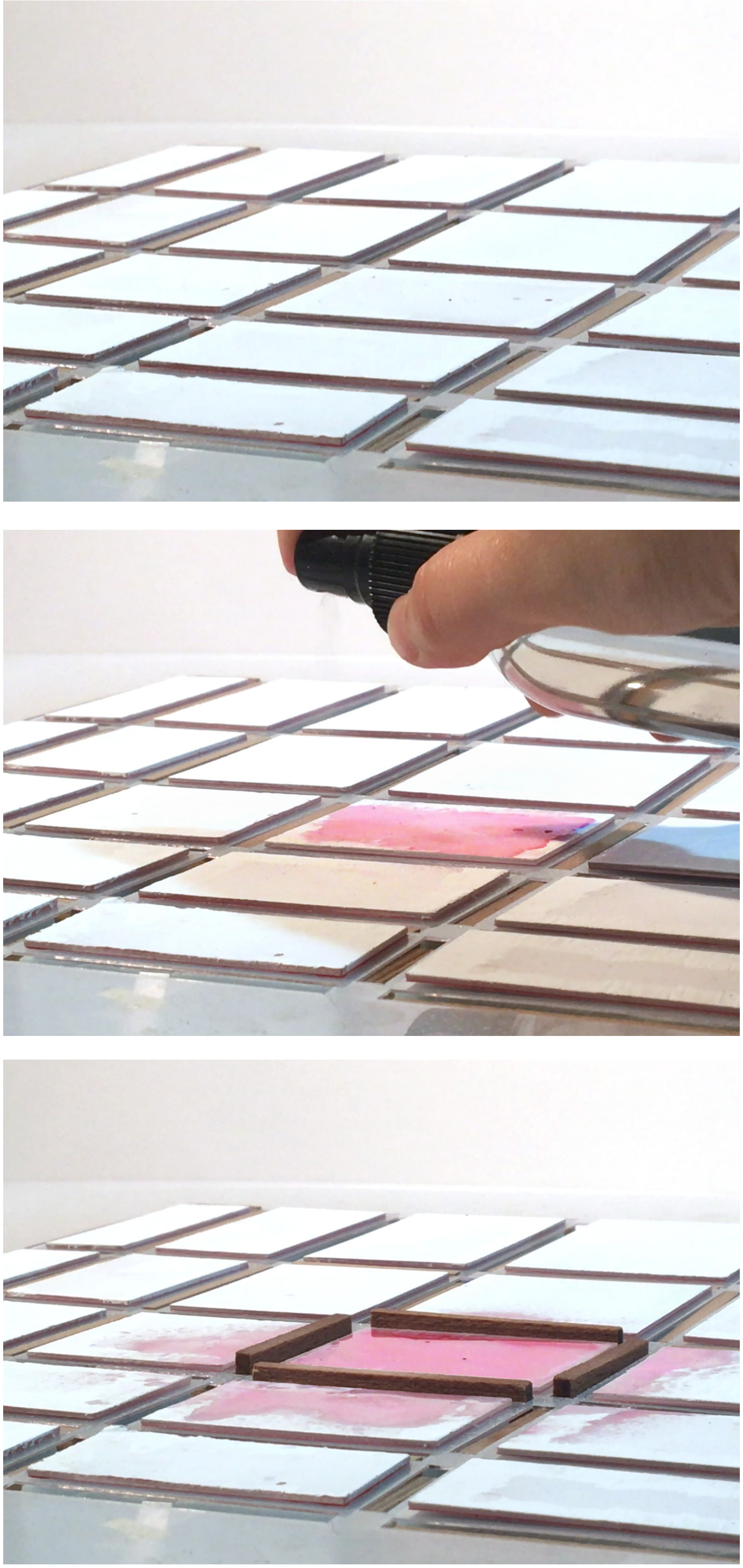
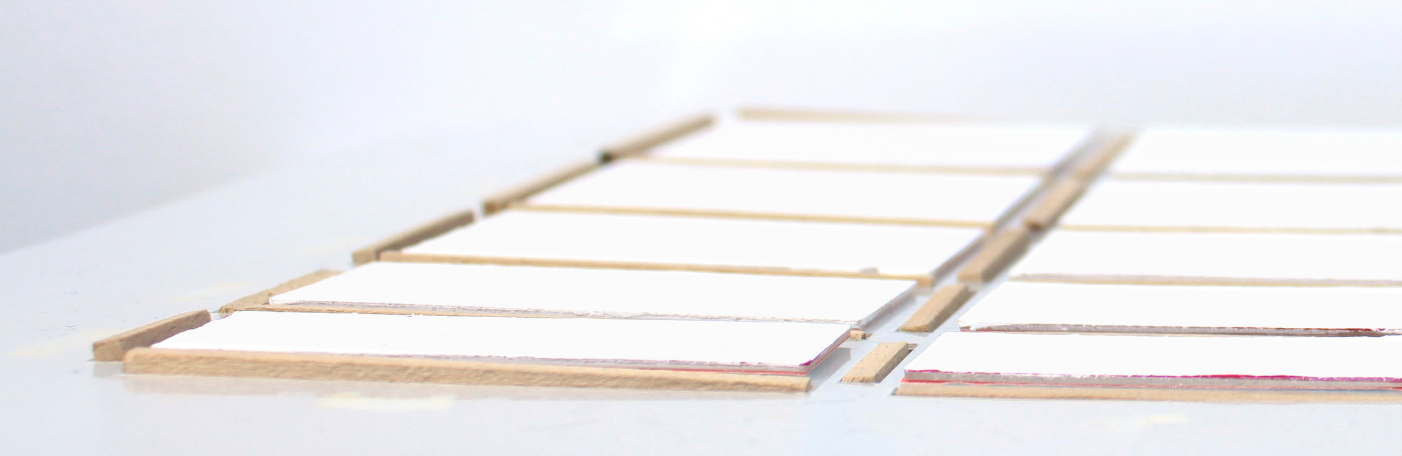
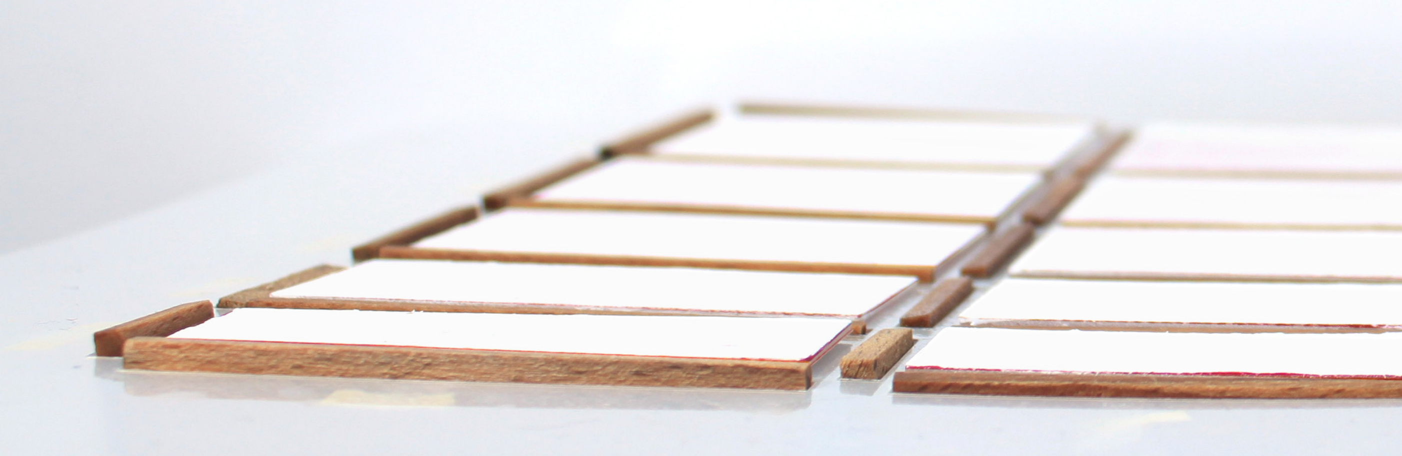
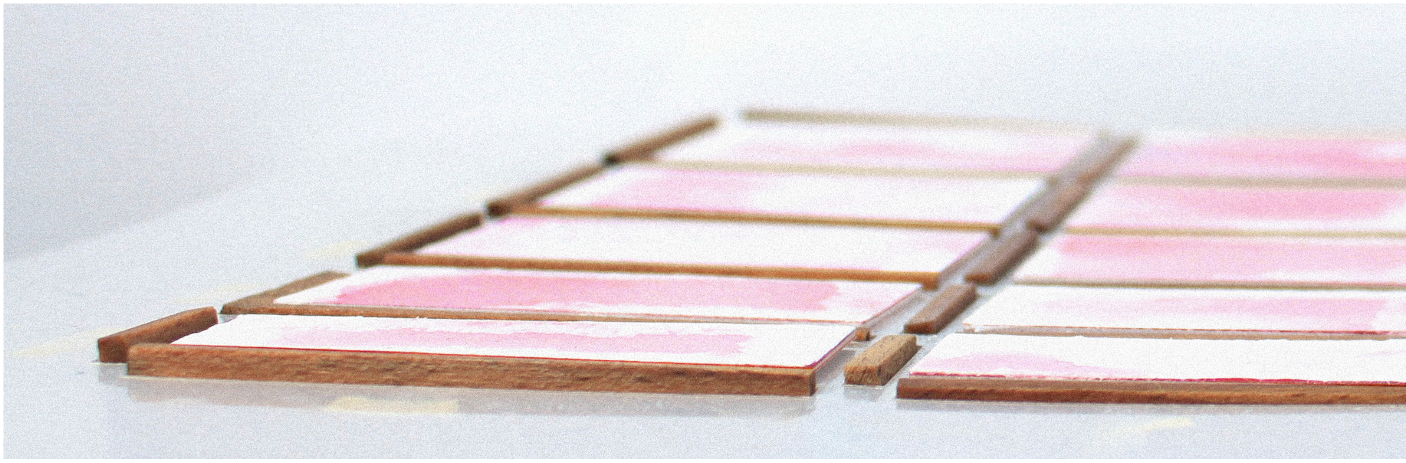


Fig.67 Proof of concept prototype for *Hydrofloor* response photo series







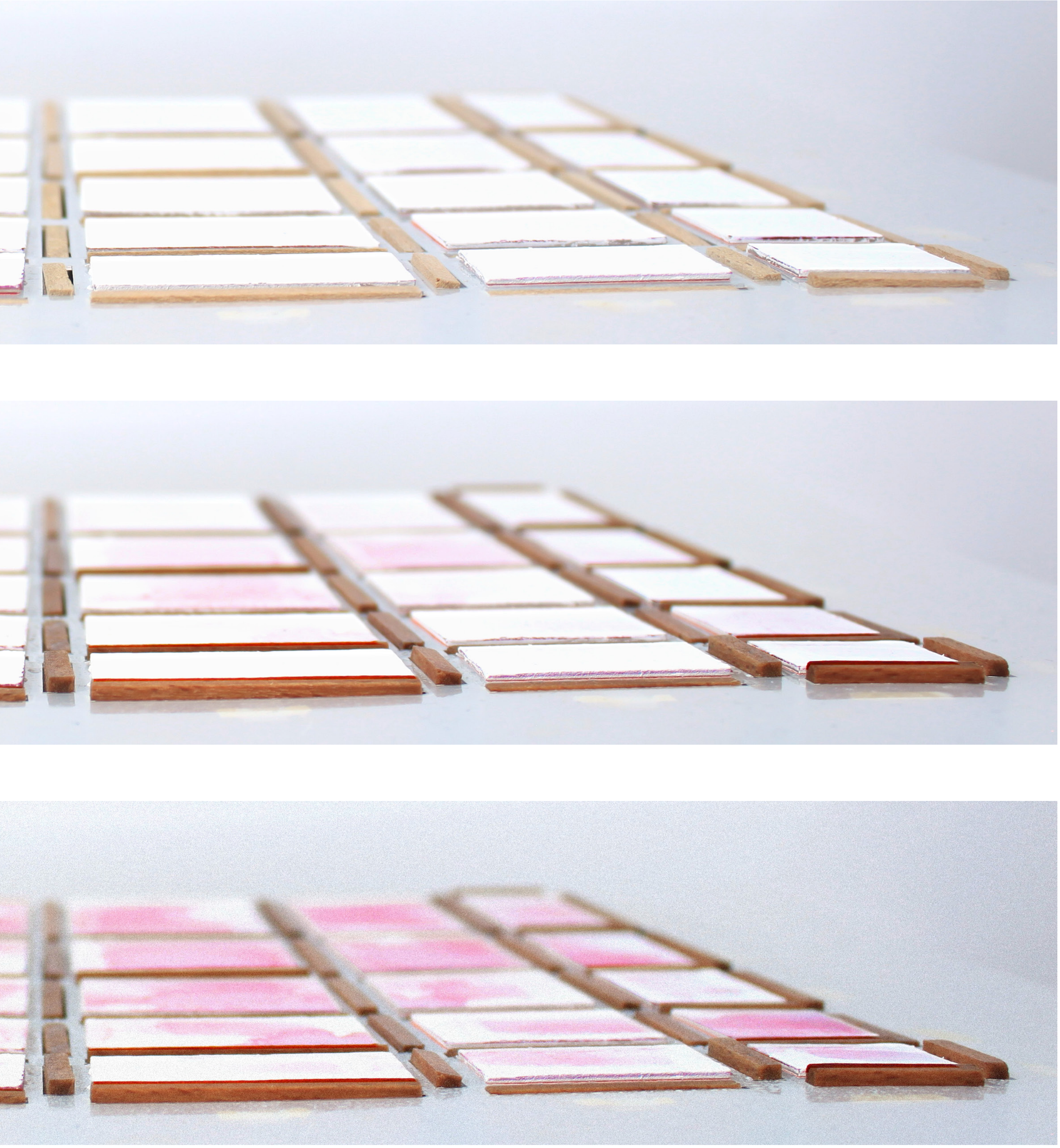


Fig.68 *Hydrofloor* Prototype

Fig.69 Renders of future application of *Hydrofloor*
Left: Exterior use to mitigate icy/snowy roads
Right: Interior use for wet zone of the house to mitigate slippage

Effect of Aging on Skin Structure

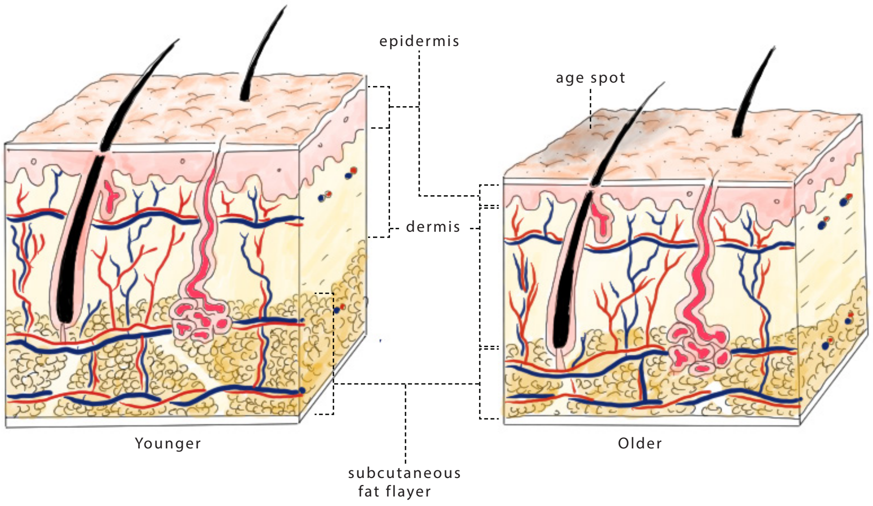
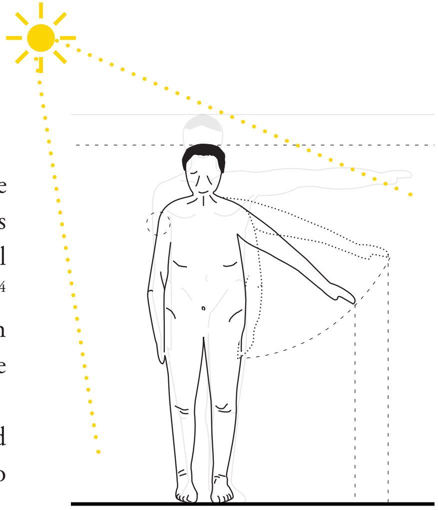


Fig.70 Normal vs Aged Skin comparison diagram [Edited by author, original Miranda A Farage et al, 2007]

Design Experiment 3:

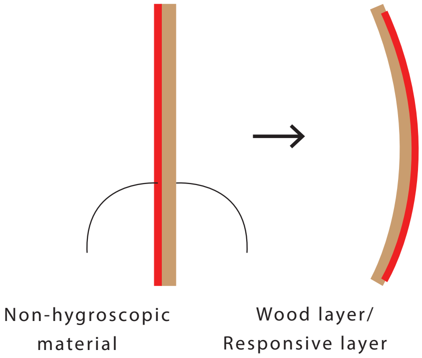
Breathing Façade



Anatomy of Thermo-regulation

Environmental thermal changes become a great health risk to us when we age because our bodies tend to lose the ability to self-regulate temperature.[113] The nervous system's sensitivity to temperature change slows with age, meaning the brain will not signal to the body to adjust its temperature until it has already reached dangerous levels.[114] This makes us more prone to severe illnesses from irregular body temperatures such as hypothermia and hyperthermia as we age.[115] Proper thermal regulation of the environment is crucial for prolonging the ability to age in place safely.

A precedent analysis of existing thermo-regulation systems shows that they had limitations of controlling solar heat gain and humidity levels and an alternative to sun-shading systems will be beneficial.



Smart material

Wood is a highly sensitive material to atmospheric changes in the environment. Similarly, to how our hair or skin responds to moisture and temperature changes, wood has an innate ability to contract and expand in response to environmental conditions. Using wood's unique sensitivity to humidity, researchers have created hygroscopic wood veneers that change shape and form in response to humidity change (Fig.71).[116] The thesis builds on previous work by the authors Reicher et al[117], and Correa et al[118], which explores hygroscopic wood veneers in constructing a climate-responsive shading system. The design experiment explores the programmatic use for hygroscopic veneer in aging in place application as a thermal regulating façade skin system.

Design Concept

The *Breathing Façade* investigates how humidity and temperature can be monitored through an architectural skin system. Responding to humidity levels in the home, the screen system self regulates the environment by effecting sun exposure, Constructed in a geometric pattern called the kirigami pattern, the façade design allows for hygroscopic movements to discreetly respond to exterior conditions but remain a single structural system (Fig.72). The façade opens up and becomes porous during cooler months to allow sunlight and closes during warmer months to provide shade. The programing of open and close states of the aperture system was designed in relation to local humidity levels throughout seasons in Toronto.[119]

The wood veneers are laminated flat at 23% relative humidity to create a screen system that will open at higher humidity levels. However, the stimulus humidity can be programmed to any relative humidity to meet needs of future applications.[120] Kirigami rules generated by Vazquez et al[121] guided the proportions of the kirigami geometry used to fabricate the prototypes. Two main aspects of study led the design experiments: the layer composition of the façade, and the resolution and scale of the apertures.

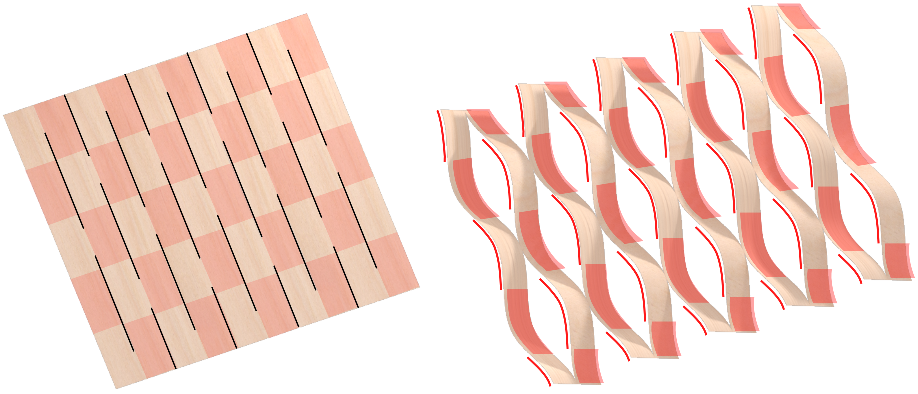


Fig.71 Top: Hygroscopic wood veneer bilayer method for dynamic curling behavior.

Fig.72 Bottom: Concept image of *Breathing facade*

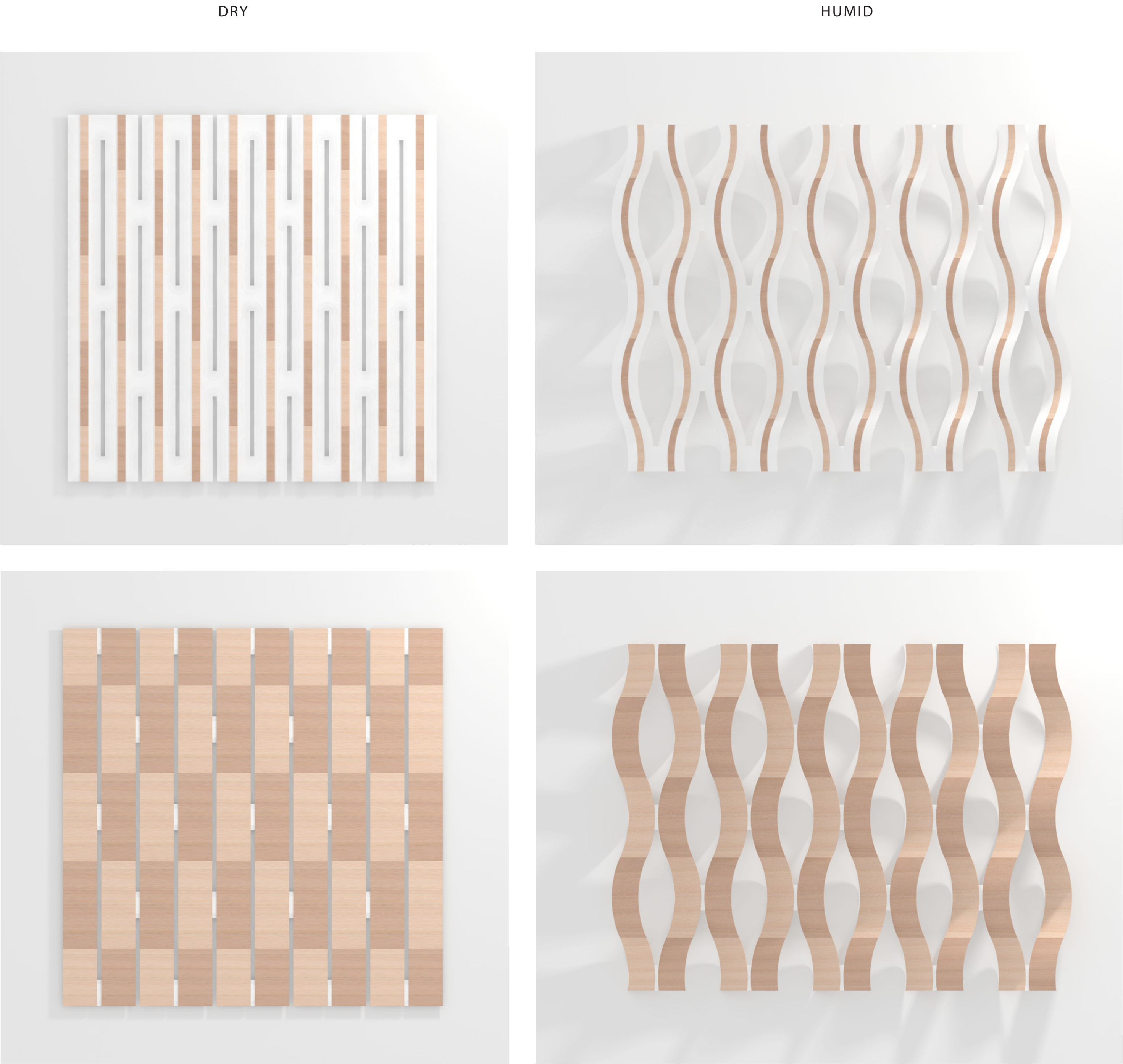
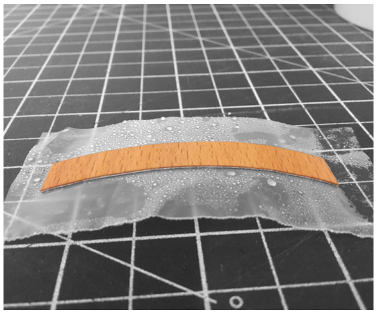


Fig.73 Render Images of *Breathing Facade* Design Concepts

Layer System



As the kirigami geometry consisted of double curvature connection points between each curve transition, wood veneer alone was not flexible enough and created weak points in these joint areas. Therefore, a flexible plastic sheet material was introduced as a base layer for the veneer system to mediate the double curvature joints. Additionally, this layer connected individual hygroscopic veneers, allowing individual responses while remaining a uniform system (Fig.74). Various layer systems were explored in the prototyping of the *Breathing Façade*. More flexible and thinner the base material was, the more it allowed the wood veneer to curl at higher rates, deforming the overall structure vertically. Thicker base material resulted in reduced vertical deformation during maximum curvatures, therefore, was chosen as it better maintained the rigidity of the system (Fig.76 & 77).

Fig.74 Detail image showing the double curvature points achieved through flexible base material

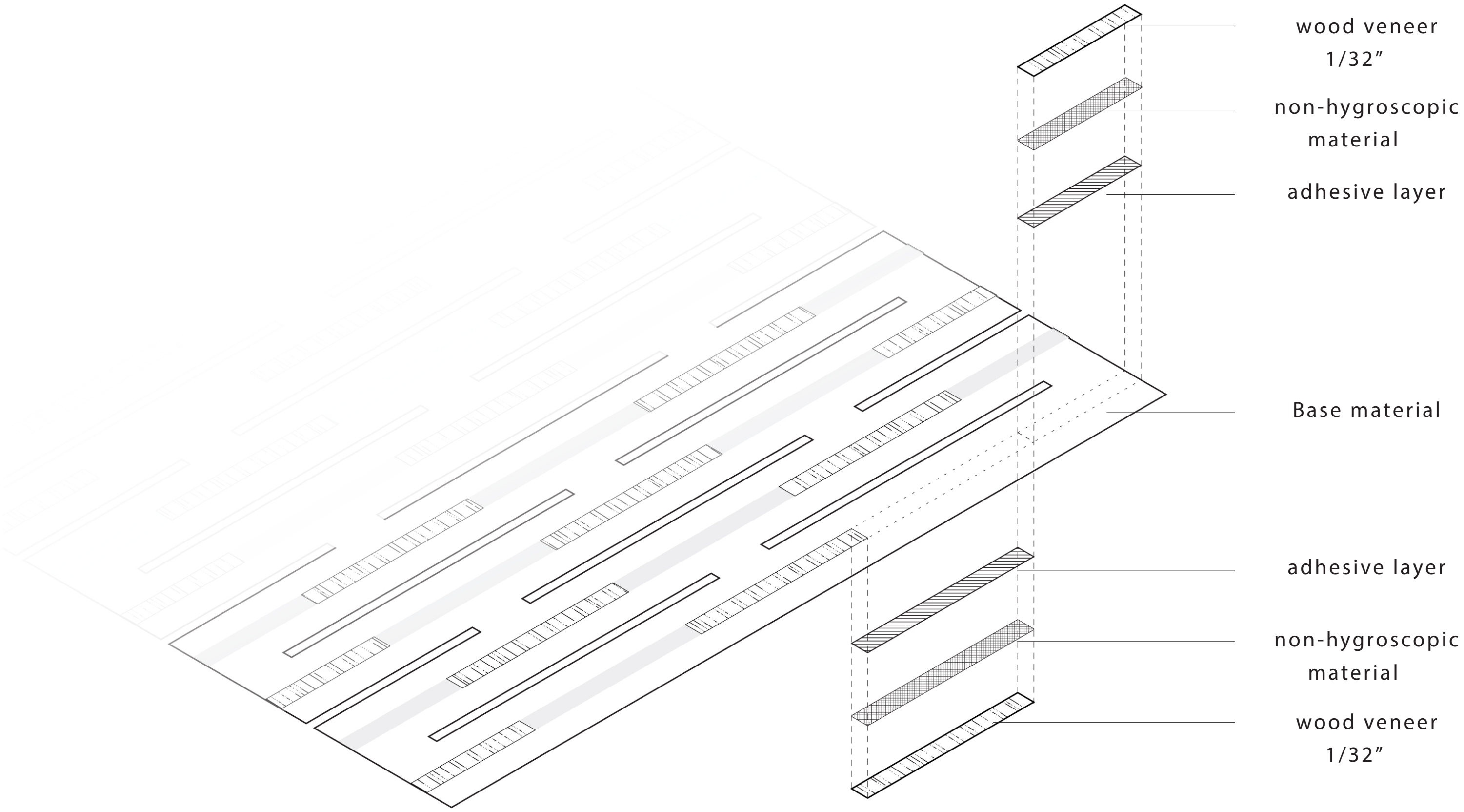
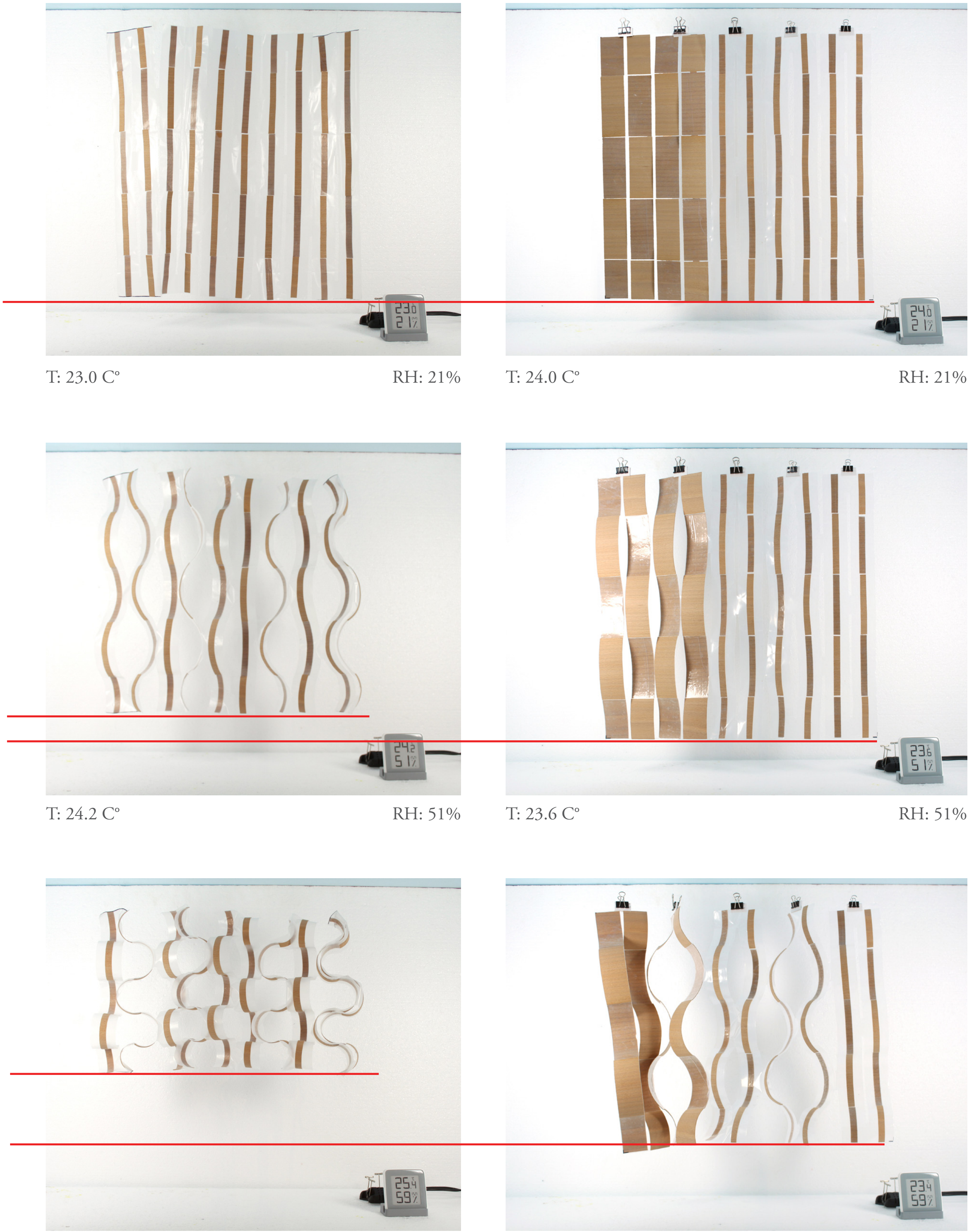


Fig.75 Assembly Drawing of *Breathing Facade* showing its layer system

Thin Base Material **Thick Base Material**



T: 23.0 C° RH: 21%

T: 24.0 C° RH: 21%

T: 24.2 C° RH: 51%

T: 23.6 C° RH: 51%

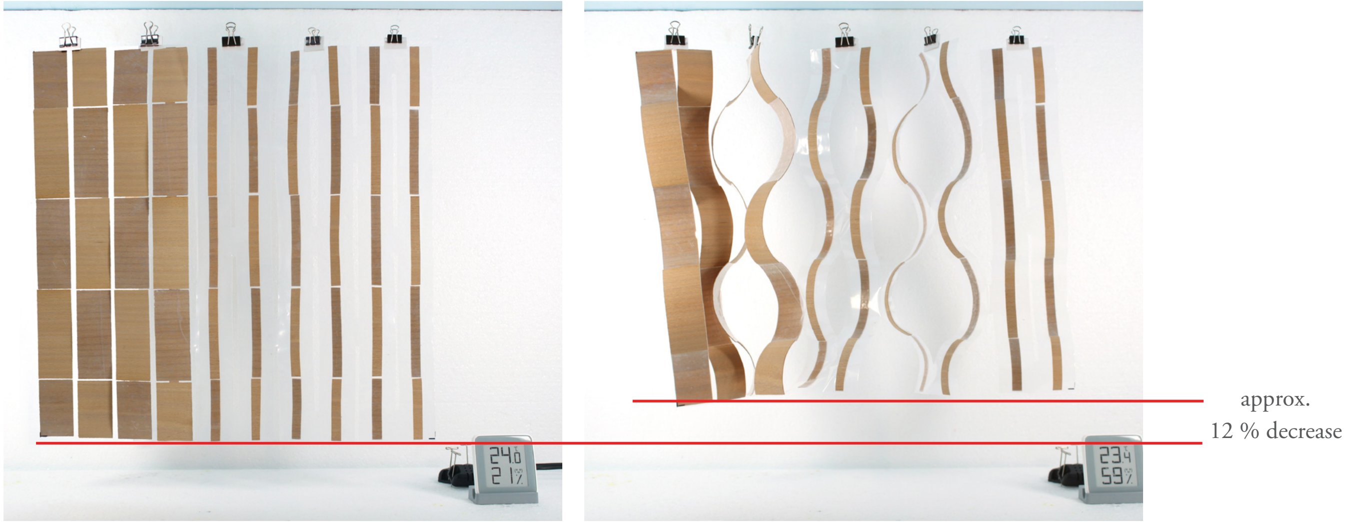
T: 25.4 C° RH: 61%

T: 23.4 C° RH: 59%

Thin Base Material

T: 23.0 C° RH: 21% T: 25.4 C° RH: 59%

Thick Base Material



T: 24.0 C° RH: 21% T: 23.4 C° RH: 59%

Fig.76 Percentage Difference between thin and thick base material

Fig.77 Percentage decrease comparison between thin and thick base material of their vertical length from closed to maximum open states

Aperture size resolution

Various scales and patterns of the screen system was explored and prototyped to showcase resolution change capacity. Resolution refers to aperture sizes of the system, the smaller the aperture the higher the resolution, the larger the aperture the lower the resolution. The response time of the hygroscopic wood resulted to be constant despite geometry change of the wood veneers (width or length), allowing for easy change of the resolution of the façade system for different needs and effects.

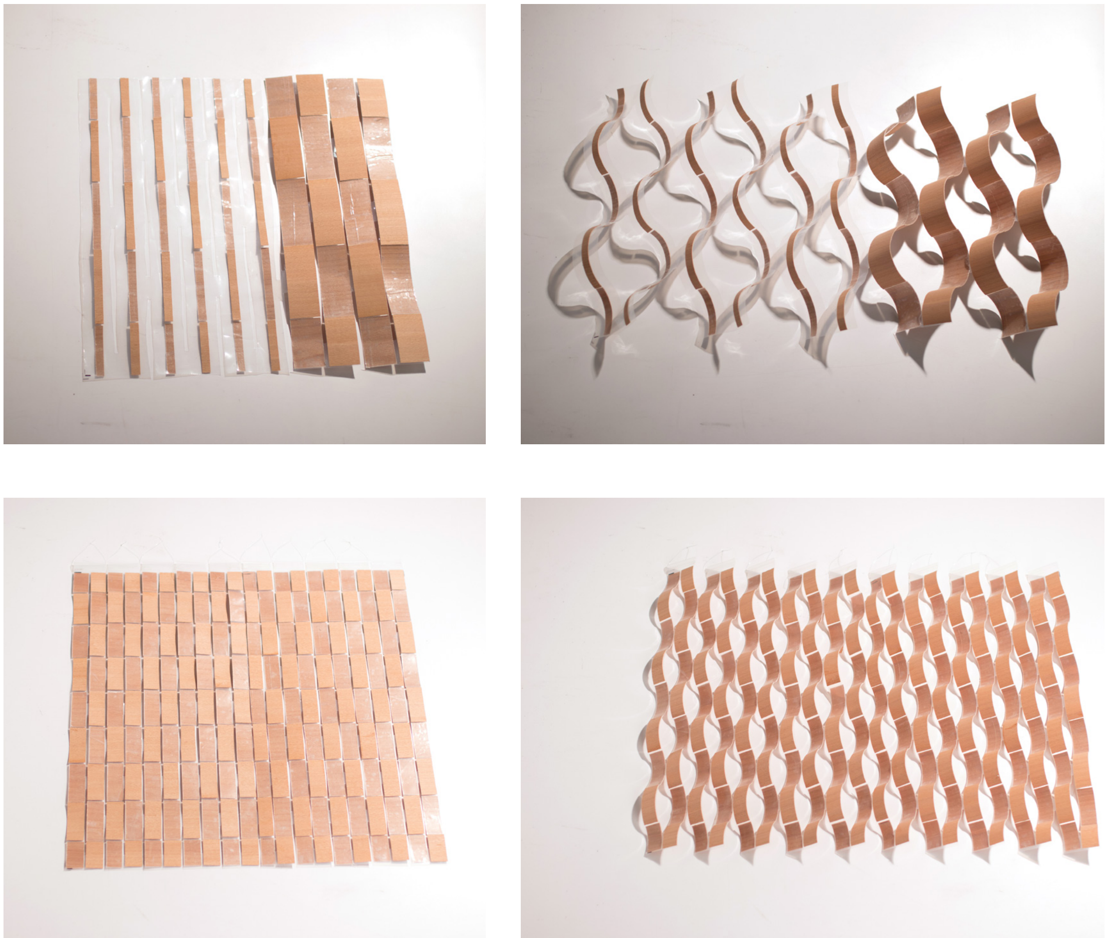
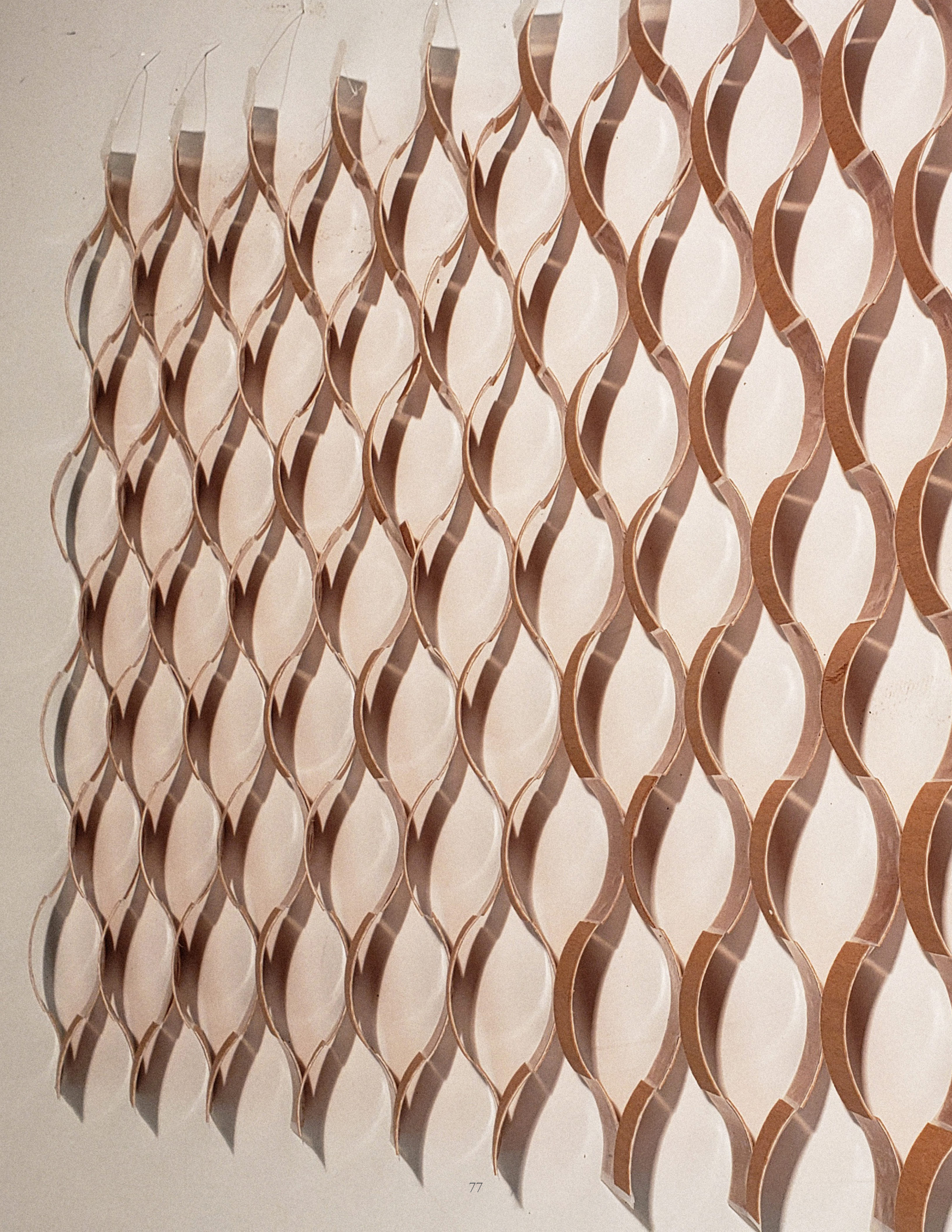


Fig.78 Left: Closed and opened states of prototype 2 and 3, showcasing different aperture size resolutions.

Fig.79 Right: Prototype 3 detail view



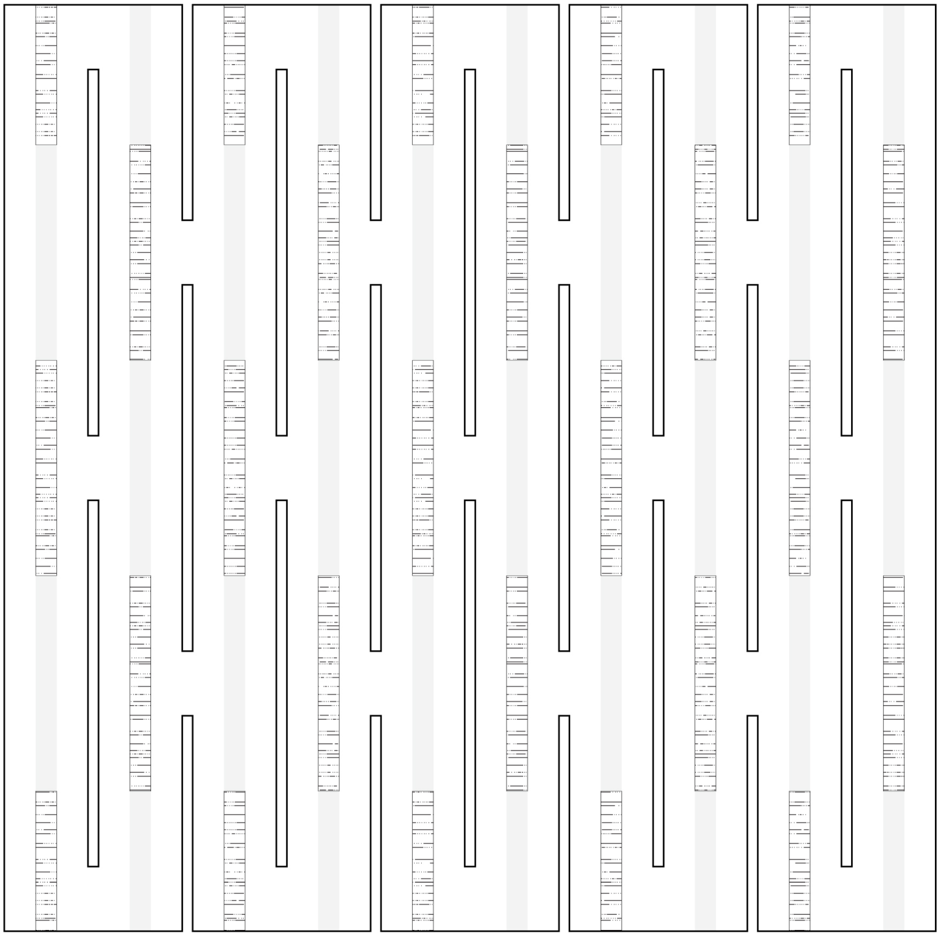
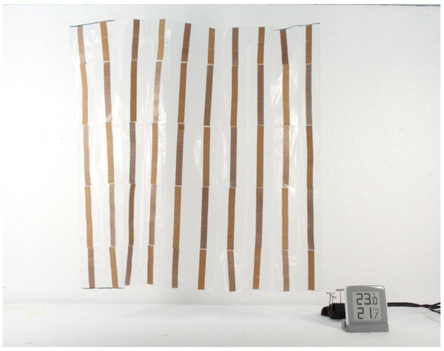


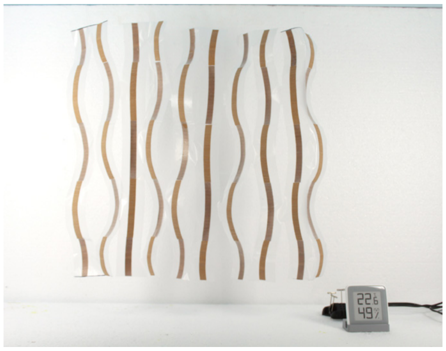
Fig.80 Left: Prototype 1 Elevation

Fig.81 Right: Time lapse photo series of Prototype 1 from close to open states.


23.0
21%


23.3
37%


22.9
45%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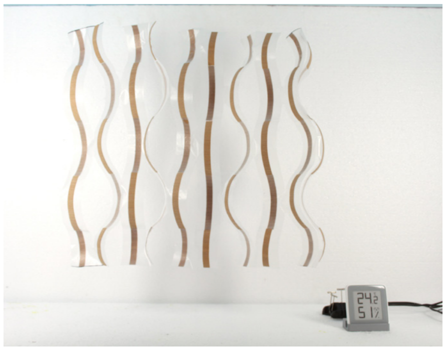
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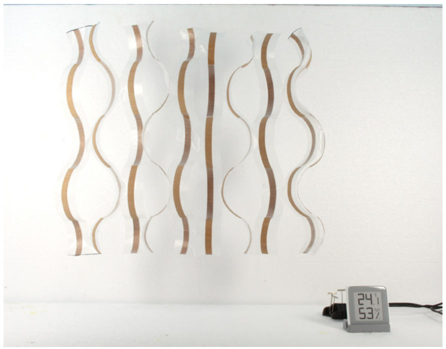
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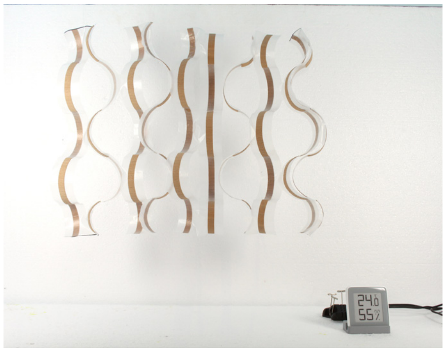
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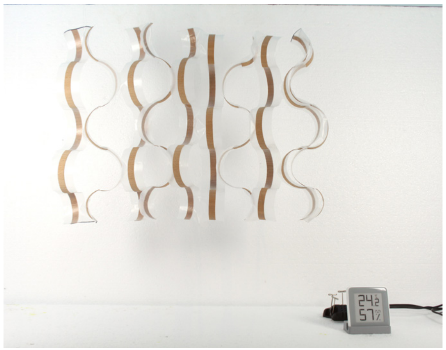
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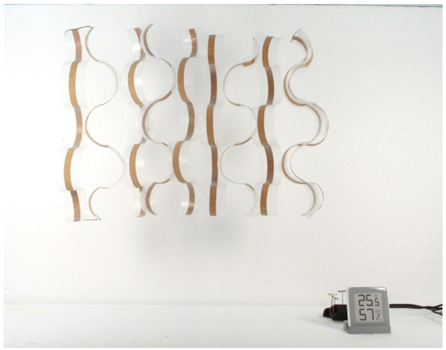
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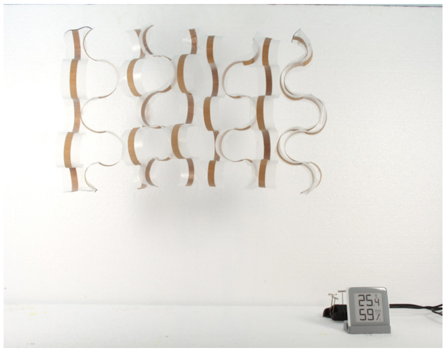
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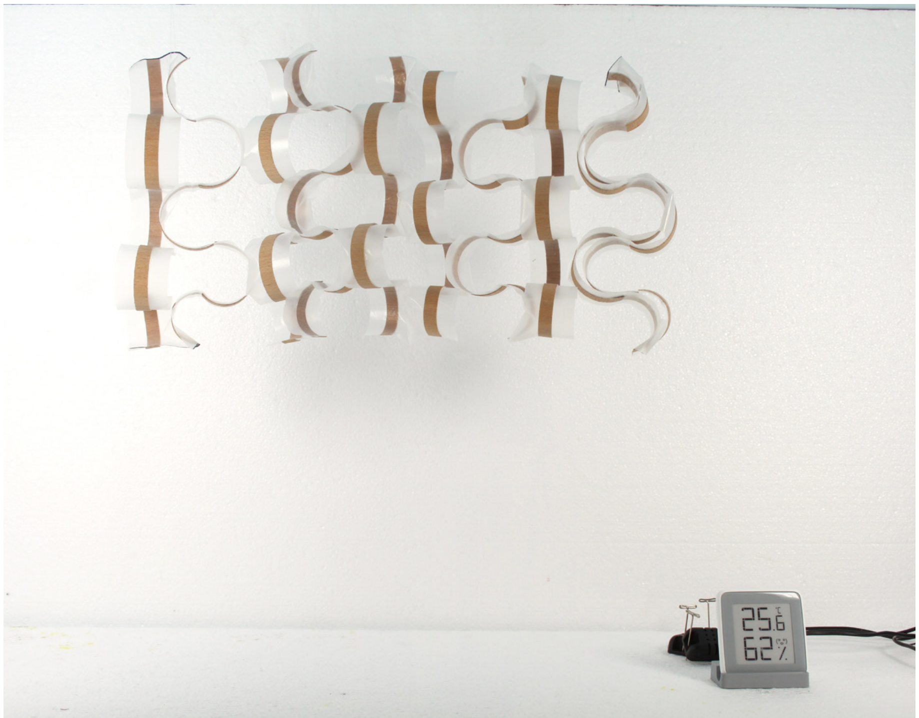
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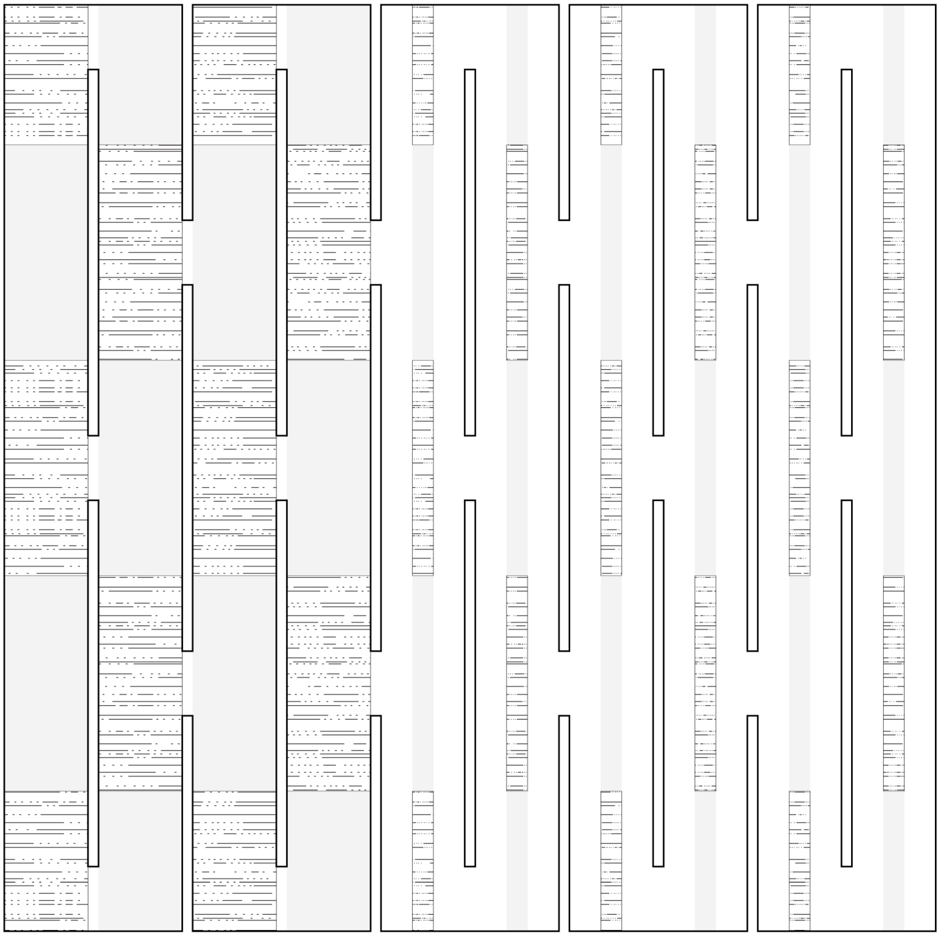
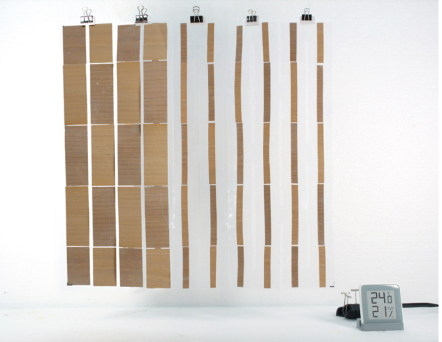


Fig.82 Left: Prototype 2 Elevation

Fig.83 Right: Time lapse photo series of Prototype 2 from close to open states.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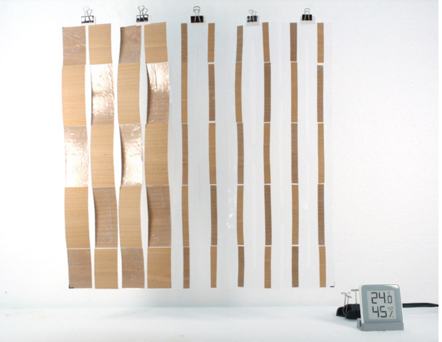
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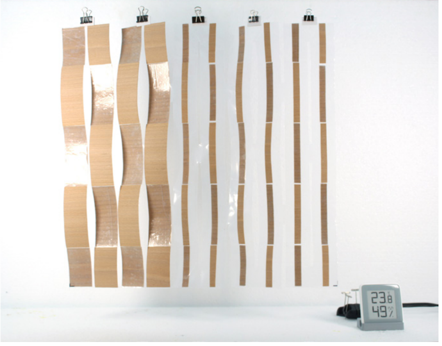
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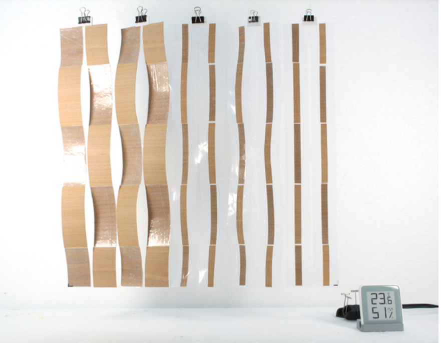
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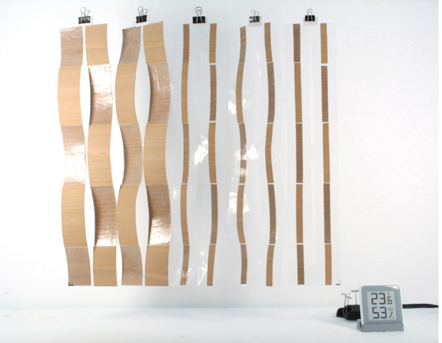
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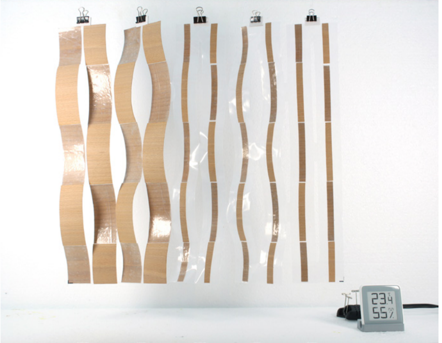
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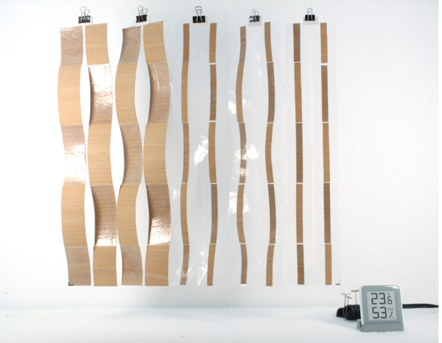
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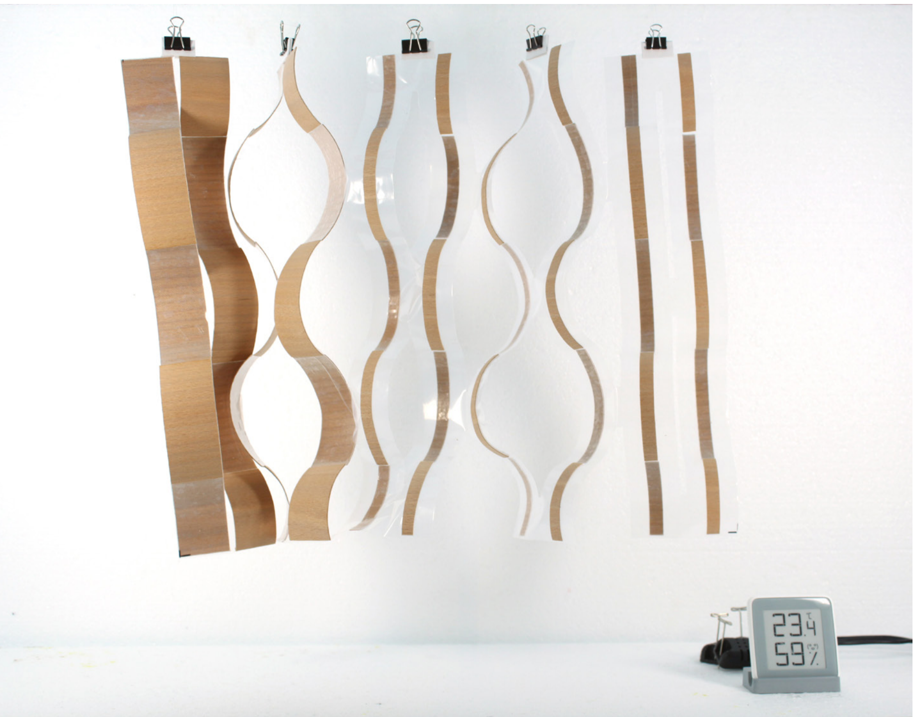
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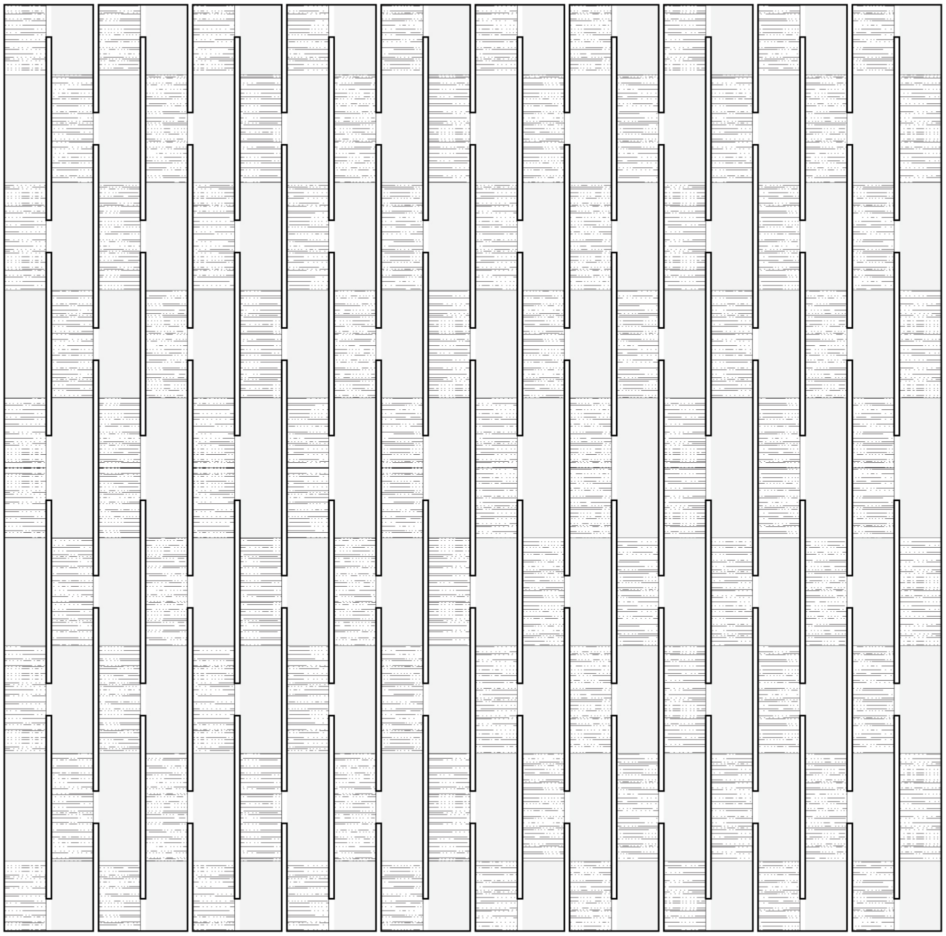
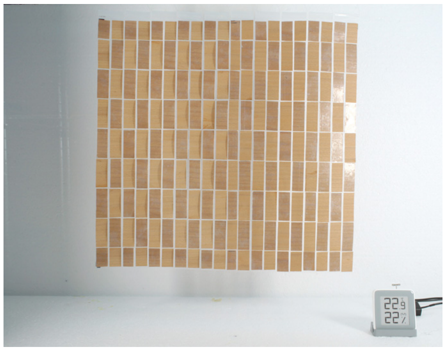


Fig.84 Left: Prototype 3 Elevation

Fig.85 Right: Time lapse photo series of Prototype 3 from close to open states.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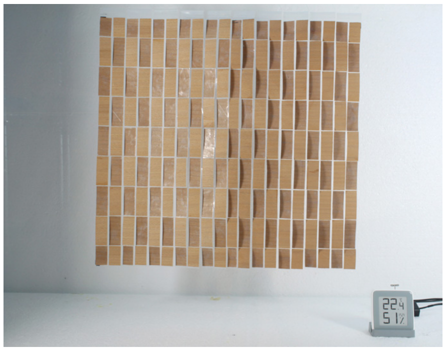
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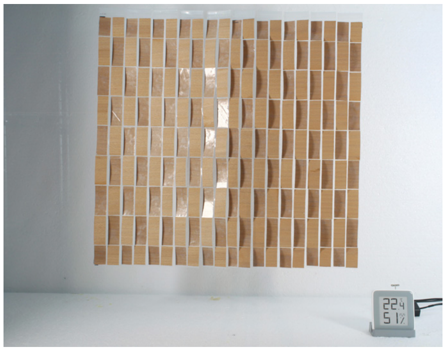
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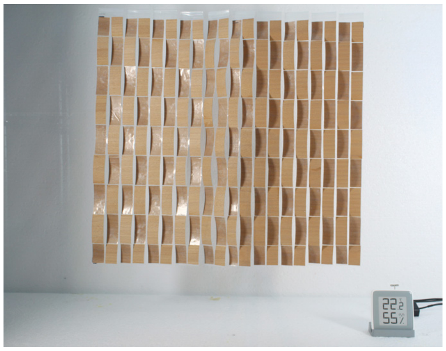
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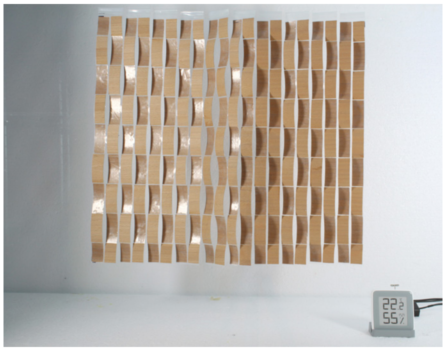
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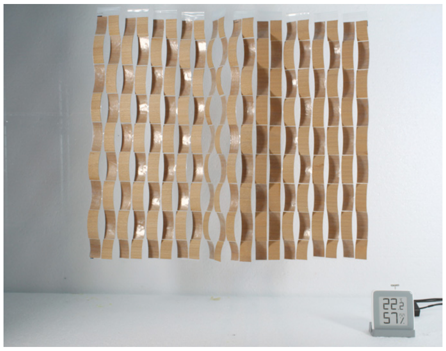
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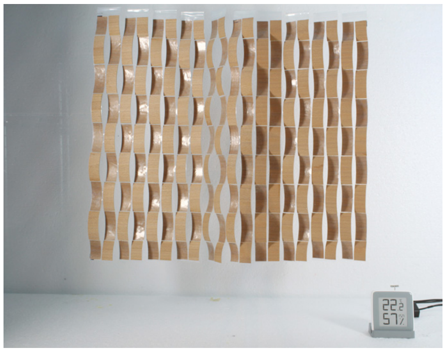
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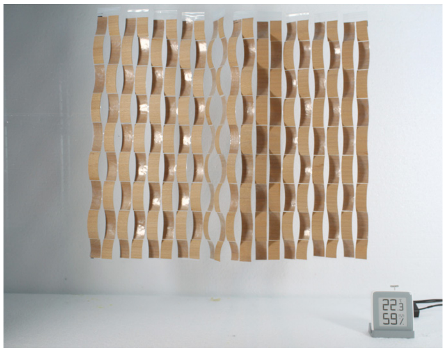
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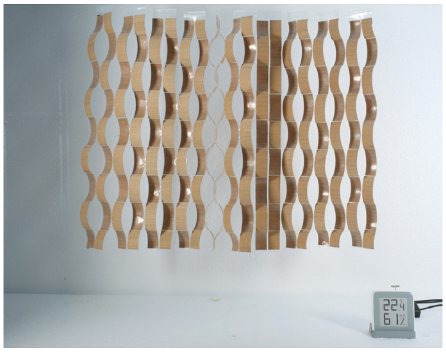
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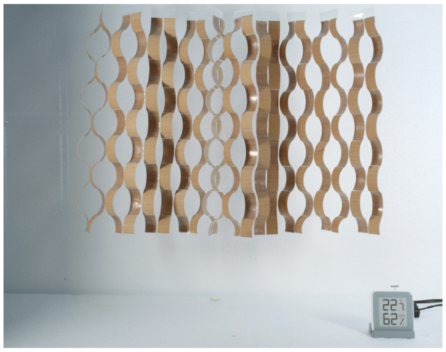
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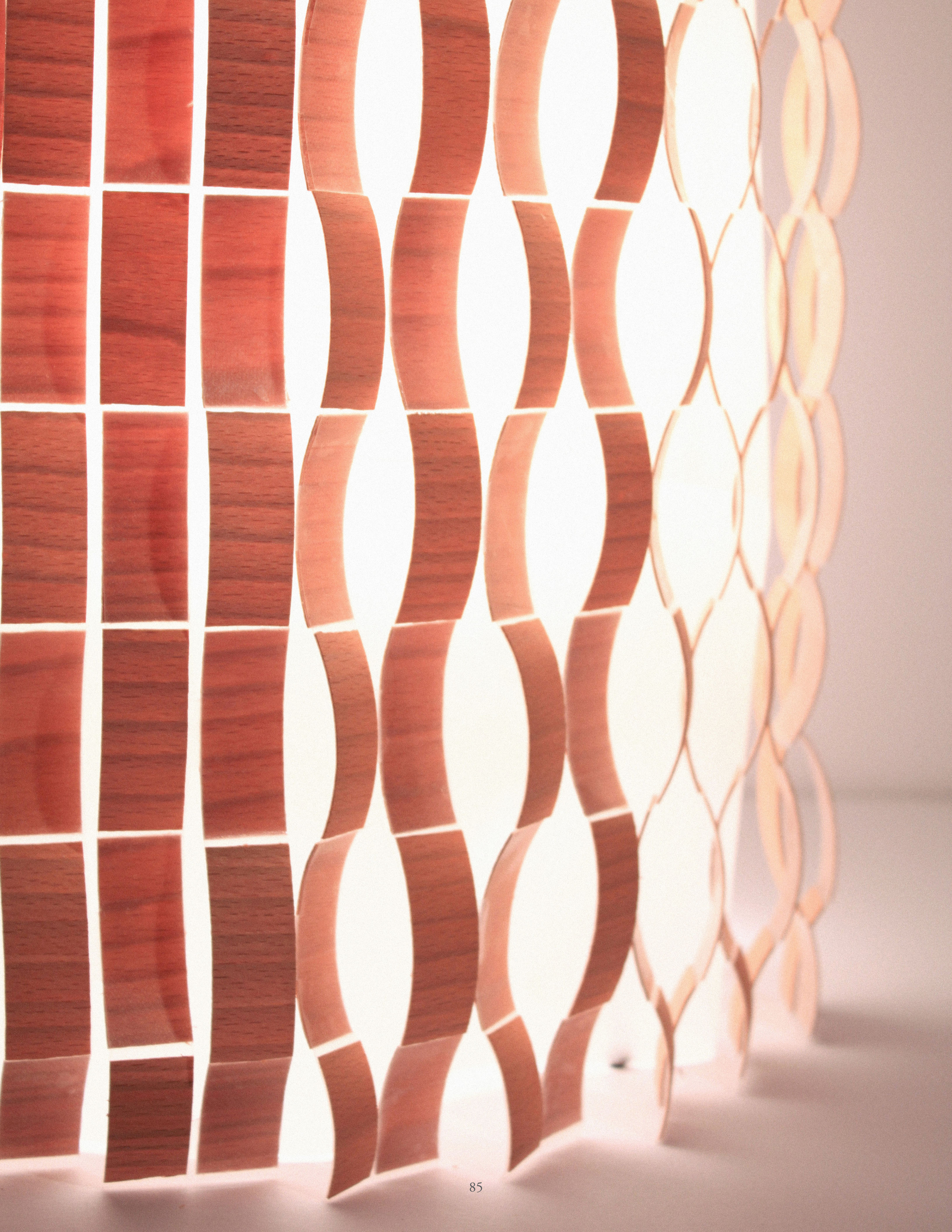
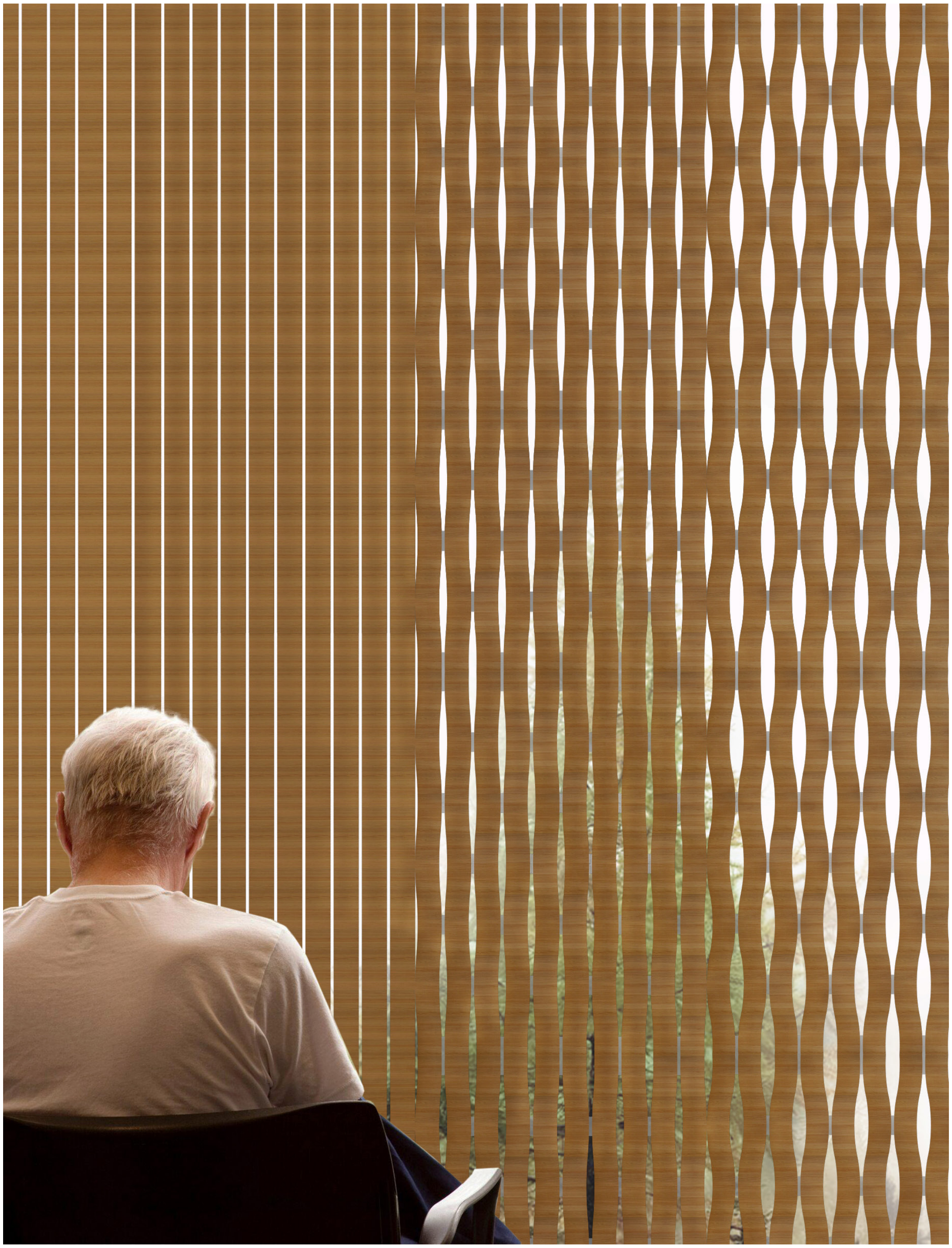
Discussion/Outlook

Exploring other base materials for the *Breathing Façade* could introduce new applications for the screen. While the current prototype consists of vapor barrier sheets as a base, further development could include structural details that allow total enclosure of the screen when it is not activated. The addition of screen meshes in the apertures that can allow air flow but maintain a barrier from the exterior of the wall could allow further humidity regulation within the environment as well as improve oxygen levels in the home. Previous literature also indicates that this material cold be integrated with other systems to regulate air flow[122] or to use radiant heat[123].

Various parameters of the façade system present potential functional qualities for further research and design. First, as the response of the hygroscopic system showed to be detached from the scale of the aperture, it indicates that the system can be comprised of different aperture sizes to provide varied conditions for the user. The façade can seamlessly transition from small aperture sizes for filtered light to large aperture sizes for higher air flow and direct sunlight, dependent on need of the user. Second, the ability to program specific stimuli humidity levels for individual hygroscopic veneers allows the façade system to respond in required areas and conditions. For instance, the façade can be programed to only open with operable windows and remain closed for solid walls, or follow sun patterns during the day for optimal shading. Moreover, the façade can be programmed custom to each room of the house, allowing varying conditions for the user. The prototype presented here, demonstrates the feasibility of the dynamic system and its potential scalability as a larger assembly. One main perceivable challenge for full scale application is the vertical and horizontal deformation of the screen system when activated. Designing of a flexible structural system that can tolerate the deformations of the screen systems will be beneficial in furthering the design application to reality.

Fig.86 Detail view of prototype 3 over light





Summer/ Dry

Winter/ Wet

Fig.87 Render Images of *Breathing Facade* during summer and winter conditions

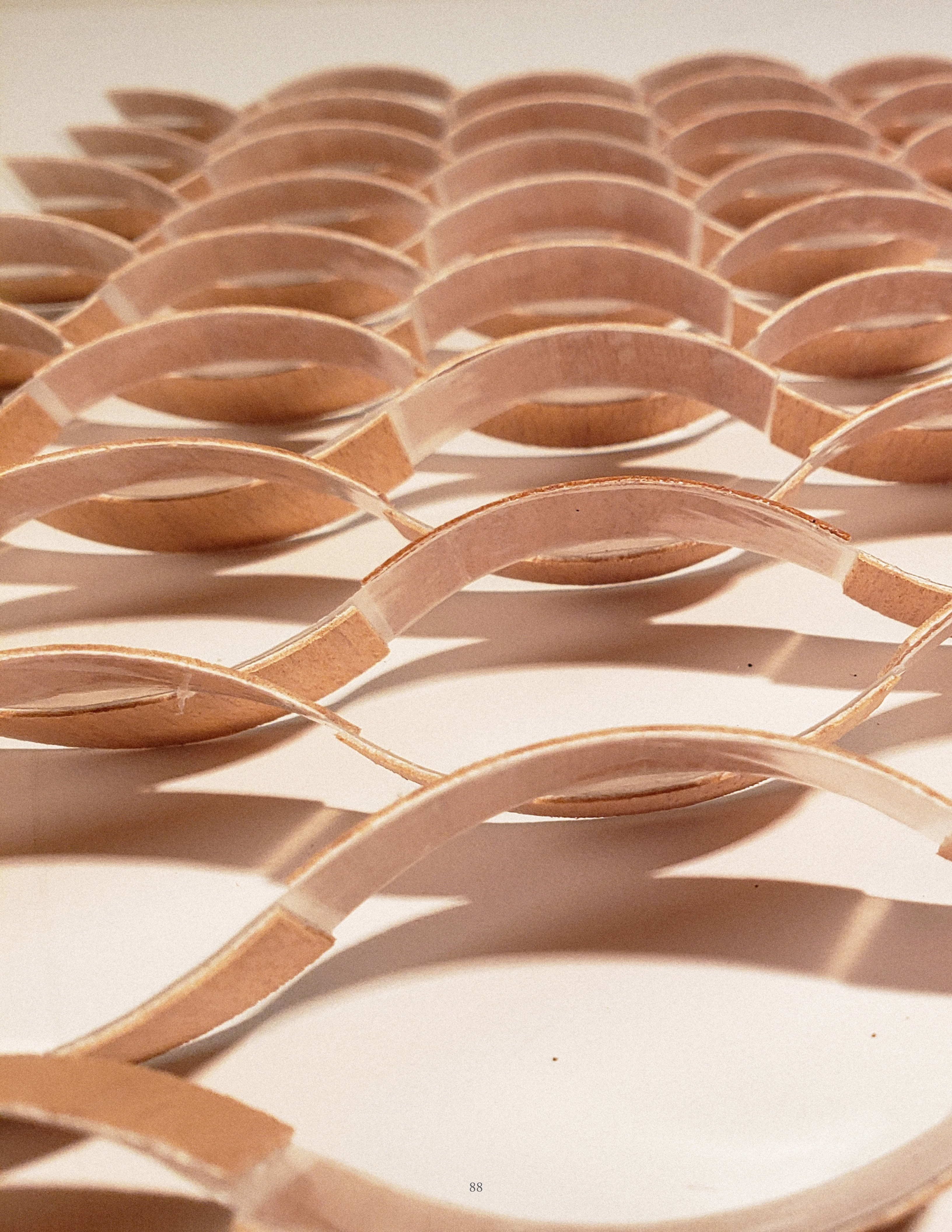


Fig.88 Detail View of *Breathing Wall*

Conclusion

Discussion/outlook

The iterative process of negotiation between user needs, material properties, and fabrication in the thesis allows for a framework of design at the intersection of aging in place and architecture. The interdisciplinary approach to design enables feedback loops between these various aspects allowing them to enrich each other and work cohesively as a system. The thesis showcases not only the potential for design to alleviate challenges of aging in place, but also how designing for marginalized user groups can innovate and inspire novel approaches for architectural design. Smart material applications in this process offer the opportunity for lost human responses and abilities to be transferred to our environment, allowing architecture to serve us as we age in place. Furthermore, through integrating qualitative needs of the user further enriched the development of smart material applications within the design experiments. For instance, in design experiment 1, *Auxetic Apparel*; requirements for user comfort inspired a functional gradation approach to the auxetic material system, further advancing its efficiency and material behaviors.

The methodology of the thesis involves identifying design problems of aging in place, designing smart material applications to alleviate identified challenges, and making of proof of concept prototypes of those designs. Further development is required to evaluate and ensure their overall success. Development of large-scale prototypes of the design experiments will allow for better testing of their performance, in both user needs and material properties. In this testing, collaboration with experts of other fields will be beneficial in developing qualitative and quantitative analysis for evaluation. Working with engineers, for example, can generate a thorough analysis of material properties to evaluate their performance and identify weak points in the design. This analysis can provide quantitative data that can validate concepts, compare and analyze different iterations, and guide further new iterations and improvements in the smart materials researched. Qualitative user testing of the designs developed in the thesis will also provide valuable insight in evaluating the quality, desirability, and functionality, while also providing deeper understanding of user affordances. Through results of the analysis, further iteration and design loops can be formed to advance the design developments of each design experiments within the thesis.

The design approach and methodology developed in the thesis can be further used as a framework for design to alleviate other challenges of aging in place beyond the scope of the thesis. Moreover, the general framework can be used as a precedent in designing smart material applications for other marginalized groups, as well as a method in finding smart material applications in architecture in general. The thesis presents a workflow that allows designs to be informed of multiple aspects such as the user and the material, allowing a well-rounded design that caters to both function and use.

Conclusion

As new problems arise in our society, the role of architecture should be consistently at a shift, adapting and enhancing to meet the needs of the society. Architects have the potential to actively provoke and seek change in our ways of life through the environment, actively shaping our future. In initiating this change, we must not only put efforts in designing solutions but first in identifying the problems we need to design for. Addressing current issues in society such as aging in place as focal points of design, it brings deeper insights into the needs of our occupants allowing us to better cater and provide essential developments for the people. Within this process, application of new technology and tools play a crucial role in providing new abilities and solutions for our environments, reshaping what architecture can provide.

This thesis advances understanding of aging in place by investigating user challenges in relation to architecture, adopting smart materials for inclusivity, and creating a new approach to design for aging in place in architecture. It proposes solutions that allow architecture to go beyond static environments and begin to adapt and respond to crucial user needs. The designs demonstrate a kind of inclusive design practice that no longer relies on standardizations of architecture to ensure accommodation for all. By designing for specific requirements and needs of marginalized user groups, the design experiments also address shared challenges of all users such as falling, slipping, and thermo-regulation.

While inclusive design and advancements of smart materials do not commonly intersect in research and design, the thesis looks at their intersection to generate innovation in advancements in architectural design that come with real implications of societal change. Their cross pollination of disciplines through the field of architecture, equips designers to address new problems that arise in our society with new solutions that we have at our disposal. Rather than advancing life of those who already find comfort in their environments, we have the opportunity to make quality of life equal and better for those who are often marginalized in our society and through it further generate innovation. The work of this thesis demonstrates the critical role the user, the material, and the tool can have in architectural design, where together, architecture can become active agents in shaping our environments to better the experience for all.

References

1 Daniel Murman, “The Impact of Age on Cognition,” *Seminars in Hearing* 36, no. 03 (July 9, 2015): 111–21, https://doi.org/10.1055/s-0035-1555115; Todd Manini, “Development of Physical Disability in Older Adults,” *Current Aging Science* 4, no. 3 (December 2011): 184–91, https://doi.org/10.2174/1874609811104030184; Jonas Andersson, “Architecture and Ageing : On the Interaction between Frail Older People and the Built Environment” (PhD Thesis, 2011)., pg.74

2 Gregory R. Jackson, Cynthia Owsley, and Gerald McGwin, “Aging and Dark Adaptation,” *Vision Research* 39, no. 23 (November 1999): 3975–82, https://doi.org/10.1016/S0042-6989(99)00092-9.

3 Joe Verghese et al., “Self-Reported Difficulty in Climbing Up or Down Stairs in Nondisabled Elderly,” *Archives of Physical Medicine and Rehabilitation* 89, no. 1 (January 2008): 100–104, https://doi.org/10.1016/j.apmr.2007.08.129.

4 Ernst. Neufert, *Architects' Data*, *Architects' Data*, 4th ed. (Chichester, West Sussex, UK ; Wiley-Blackwell, 2012); Ernst Neufert, *Architects' Data*, *Architects' Data*, Fifth English language edition. (Chichester, West Sussex: Wiley/Blackwell, 2019).

5 United Nations, “World Population Ageing 2017 /2018 - Highlights,” 2017, https://statistical.proquest.com/statisticalinsight/result/pqpresultpage.previewtitle?docType=PQSI&titleUri=/content/2018/3080-S87.xml.

6 Sotheby's International Realty Canada, “Aging in Place Report Reveals 86% of Urban Canadian Baby Boomers/Older Adult Homeowners Want to Live in Their Homes for as Long as Possible,” GlobeNewswire News Room, March 4, 2020, http://www.globenewswire.com/news-release/2020/03/04/1994809/0/en/Aging-in-Place-Report-Reveals-86-of-Urban-Canadian-Baby-Boomers-Older-Adult-Homeowners-Want-to-Live-in-their-Homes-for-as-Long-as-Possible.html.

7 Donald A. Norman, *The Design of Everyday Things*, *The Design of Everyday Things*, Revised and expanded edition. (New York: Basic Books, A Member of the Perseus Books Group, 2013).

8 K. Holmes and J. Maeda, *Mismatch: How Inclusion Shapes Design* (MIT Press, 2018), https://books.google.ca/books?id=mVHCswEACAAJ.

9 Jos Boys, *Doing Disability Differently : An Alternative Handbook on Architecture, Dis/Ability and Designing for Everyday Life* (London ; New York: Routledge, 2014).

10 Itab Shuayb, *Inclusive University Built Environments: The Impact of Approved Document M for Architects, Designers, and Engineers* (Springer Nature, 2020).

11 Ibid.

12 Ibid.

13 Ibid.

14 Ibid. pg.11

15 Judith A. Davey et al., "Accommodation Options for Older People in Aotearoa/New Zealand," 2004. -pg.133

16 Ibid.

17 Jacquelyn Beth Frank, *The Paradox of Aging in Place in Assisted Living* (Westport, Conn: Bergin & Garvey, 2002); Robyn Gibbard, "Sizing Up the Challenge: Meeting the Demand for Long-Term Care in Canada" (The Conference Board of Canada, November 27, 2017).

18 Canadian Institute for Health Information, "Seniors in Transition: Exploring Pathways Across the Care Continuum" (Ottawa: Canadian Institute for Health Information, 2017).

19 Ibid.

20 Susan M. Goltsman and Daniel S. Iacofano, eds., *The Inclusive City: Design Solutions for Buildings, Neighborhoods and Urban Spaces* (Berkeley, Calif: MIG Communications, 2007).

21 Ibid.

22 Bettye Rose Connell et al., "The Center for Universal Design - Universal Design Principles," 1997, https://projects.ncsu.edu/ncsu/design/cud/about_ud/udprinciplestext.htm; Hans Persson et al., "Universal Design, Inclusive Design, Accessible Design, Design for All: Different Concepts—One Goal? On the Concept of Accessibility—Historical, Methodological and Philosophical Aspects," Universal Access in the Information Society 14, no. 4 (November 1, 2015): 505–26, https://doi.org/10.1007/s10209-014-0358-z.

23 Thomas Carpentier, "Measure(s) of Man: Architects' Data Add-On," accessed July 25, 2020, https://www.thomascarpentier.com/Measure-s-of-Man-Architects-Data-Add-on.

24 Holmes and Maeda, *Mismatch: How Inclusion Shapes Design*.

25 Ibid.

26 Michael H. Adler, *The Writing Machine* (London: Allen & Unwin, 1973).

27 Jos Boys, "THE DISORDINARY ARCHITECTURE PROJECT: A Handy Guide for Doing Disability Differently in Architecture and Urban Design by Jos Boys," *THE FUNAMBULIST MAGAZINE* 19 (September 2018): 32–39.

28 Galludet University, "DeafSpace," accessed July 25, 2020, https://www.gallaudet.edu/campus-design-and-planning/deafspace.

29 Clark M. Blatteis, "Age-Dependent Changes in Temperature Regulation - a Mini Review," *Gerontology* 58, no. 4 (2012): 289–95, https://doi.org/10.1159/000333148.

30 Jackson, Owsley, and McGwin, "Aging and Dark Adaptation."

31 Holger Schnädelbach, *Adaptive Architecture - A Conceptual Framework*, 2010.

32 Robert Kronenburg, *Flexible: Architecture That Responds to Change* (London: Laurence King, 2007); Richard Harper, ed., *Inside the Smart Home* (London ; New York: Springer, 2003).

33 Schnädelbach, *Adaptive Architecture - A Conceptual Framework*.

34 Gerrit Rietveld, *Schröder House*, 1924, 1924, Utrecht,Netherlands.

35 Dillerscofidio & Renfro, "The Shed," DS+R, 2019, https://dsrny.com/project/the-shed.

36 D. Michelle Addington and Daniel L Schodek, *Smart Materials and New Technologies: For the Architecture and Design Professions*, 2016.

37 Ibid.

38 Ibid.

39 Steffen Reichert, Achim Menges, and David Correa, "Meteorosensitive Architecture: Biomimetic Building Skins Based on Materially Embedded and Hygroscopically Enabled Responsiveness," *Computer-Aided Design* 60 (March 2015): 50–69, https://doi.org/10.1016/j.cad.2014.02.010.

40 "Bloom | DOSU Studio," accessed July 30, 2020, https://www.dosu-arch.com/bloom.

41 Elena Vazquez, Clive Randall, and Jose Pinto Duarte, "Shape-Changing Architectural Skins: A Review on Materials, Design and Fabrication Strategies and Performance Analysis," *Journal of Facade Design and Engineering*, December 24, 2019, 91-102 Pages, https://doi.org/10.7480/JFDE.2019.2.3877.

42 Michelle Addington, "Magic or Material," *Perspecta* 42 (2010): 199–204.

43 David Correa et al., "3D-Printed Wood: Programming Hygroscopic Material Transformations," *3D Printing and Additive Manufacturing* 2, no. 3 (September 2015): 106–16, https://doi.org/10.1089/3dp.2015.0022; Skylar Tibbits, "Design to Self-Assembly," *Architectural Design* 82, no. 2 (March 2012): 68–73, https://doi.org/10.1002/ad.1381; Shida Miao et al., "4D Printing of Polymeric Materials for Tissue and Organ Regeneration," *Materials Today* 20, no. 10 (December 2017): 577–91, https://doi.org/10.1016/j.mattod.2017.06.005.

44 Tibbits, "Design to Self-Assembly."

45 Correa et al., "3D-Printed Wood."

46 Neri Oxman, "Material-Based Design Computation" (Massachusetts Institute of Technology. Dept. of Architecture., 2010), http://hdl.handle.net/1721.1/59192; Neri Oxman, "Variable Property Rapid Prototyping," *Virtual and Physical Prototyping* 6, no. 1 (2011): 3–31, https://doi.org/10.1080/17452759.2011.558588.

47 Lining Yao et al., “BioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces,” in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI ’15* (the 33rd Annual ACM Conference, Seoul, Republic of Korea: ACM Press, 2015), 1–10, https://doi.org/10.1145/2702123.2702611.

48 Jenny Sabin, “Lumen,” Jenny Sabin Studio, September 4, 2017, https://www.jennysabin.com/lumen.

49 Ibid.

50 G. Williams, *Applied Qualitative Research Design* (EDTECH, 2019), https://books.google.ca/books?id=ueLEDwAAQBAJ.

51 Glen Hougan, “Senior Centered Adaptations: Product Hacking in the Home” (DSA International Conference, Chicago: white paper, 2013), https://nscad.academia.edu/GlenHougan/Papers.

52 Ibid.

53 IDEO, ed., *The Field Guide to Human-Centered Design: Design Kit*, 1st. ed (San Francisco, Calif: IDEO, 2015).

54 Williams, *Applied Qualitative Research Design*.

55 Norman, *The Design of Everyday Things*.

56 National Council on Aging, “Falls Prevention Facts,” NCOA, June 3, 2015, https://www.ncoa.org/news/resources-for-reporters/get-the-facts/falls-prevention-facts/.

57 R. Sean Morrison, “The Medical Consultant’s Role in Caring for Patients with Hip Fracture,” *Annals of Internal Medicine* 128, no. 12_Part_1 (June 15, 1998): 1010, https://doi.org/10.7326/0003-4819-128-12_Part_1-199806150-00010.

58 N. M. van Schoor et al., “Acceptance and Compliance with External Hip Protectors: A Systematic Review of the Literature,” *Osteoporosis International* 13, no. 12 (December 1, 2002): 917–24, https://doi.org/10.1007/s001980200128.

59 Ibid.

60 Susan J. Blalock et al., "SENIORS' PERCEPTIONS OF USING HIP PROTECTORS TO REDUCE FRACTURE RISK: LETTERS TO THE EDITOR," *Journal of the American Geriatrics Society* 56, no. 9 (September 2008): 1773–74, https://doi.org/10.1111/j.1532-5415.2008.01868.x.

61 van Schoor et al., "Acceptance and Compliance with External Hip Protectors."

62 A. Bueno-Cavanillas et al., "Risk Factors in Falls among the Elderly According to Extrinsic and Intrinsic Precipitating Causes," *European Journal of Epidemiology* 16, no. 9 (2000): 849–59, https://doi.org/10.1023/A:1007636531965.

63 American Family Physician, "What Causes Falls in the Elderly? How Can I Prevent a Fall?," *American Family Physician* 61, no. 7 (April 1, 2000): 2173.

64 Bueno-Cavanillas et al., "Risk Factors in Falls among the Elderly According to Extrinsic and Intrinsic Precipitating Causes."

65 S.E. Tomlinson et al., "Human Finger Friction in Contacts with Ridged Surfaces," *Wear* 301, no. 1–2 (April 2013): 330–37, https://doi.org/10.1016/j.wear.2012.12.039.

66 Alexa K. Doig and Janice M. Morse, "The Hazards of Using Floor Mats as a Fall Protection Device at the Bedside:," *Journal of Patient Safety* 6, no. 2 (June 2010): 68–75, https://doi.org/10.1097/PTS.0b013e3181cb439a.

67 Margaret Stevens, C. D'Arcy J. Holman, and Nicole Bennett, "Preventing Falls in Older People: Impact of an Intervention to Reduce Environmental Hazards in the Home," *Journal of the American Geriatrics Society* 49, no. 11 (November 2001): 1442–47, https://doi.org/10.1046/j.1532-5415.2001.4911235.x.

68 Jonathan A. Patz et al., "Impact of Regional Climate Change on Human Health," *Nature* 438, no. 7066 (November 2005): 310–17, https://doi.org/10.1038/nature04188.

69 Jonathan A. Patz et al., "Climate Change: Challenges and Opportunities for Global Health," *JAMA* 312, no. 15 (October 15, 2014): 1565, https://doi.org/10.1001/jama.2014.13186; Jonathan A. Patz and Mahmooda Khaliq, "MSJAMA: Global Climate Change and Health: Challenges for Future Practitioners.," *JAMA* 287, no. 17 (May 1, 2002): 2283–84; Nick Watts et al., "Health and Climate Change: Policy Responses to Protect Public Health," *The Lancet* 386, no. 10006 (November 2015): 1861–1914, https://doi.org/10.1016/S0140-6736(15)60854-6.

70 Jean-Marie Robine et al., "Death Toll Exceeded 70,000 in Europe during the Summer of 2003," *Comptes Rendus Biologies* 331, no. 2 (February 2008): 171–78, https://doi.org/10.1016/j.crvi.2007.12.001.

71 George Havenith et al., "Age Predicts Cardiovascular, but Not Thermoregulatory, Responses to Humid Heat Stress," *European Journal of Applied Physiology and Occupational Physiology* 70, no. 1 (1995): 88–96, https://doi.org/10.1007/BF00601814; Y. Inoue et al., "Exercise- and Methylcholine-Induced Sweating Responses in Older and Younger Men: Effect of Heat Acclimation and Aerobic Fitness," *International Journal of Biometeorology* 42, no. 4 (March 29, 1999): 210–16, https://doi.org/10.1007/s004840050107; WR Keatinge et al., "Cold Exposure and Winter Mortality from Ischaemic Heart Disease, Cerebrovascular Disease, Respiratory Disease, and All Causes in Warm and Cold Regions of Europe," *The Lancet* 349 (1997): 1341–46.

72 Michael Miller, *My Smart Home for Seniors*, My...for Seniors (Indianapolis, Indiana: QUE, Pearson Education, Inc, 2017).

73 Ibid.

74 Blatteis, "Age-Dependent Changes in Temperature Regulation - a Mini Review."

75 Michael A. Ferenczi et al., "Why Muscle Is an Efficient Shock Absorber," ed. Laszlo Csernoch, *PLoS ONE* 9, no. 1 (January 23, 2014): e85739, https://doi.org/10.1371/journal.pone.0085739.

76 Ibid.

77 National Council on Aging, "Falls Prevention Facts."

78 Oddom Demontiero, Christopher Vidal, and Gustavo Duque, "Aging and Bone Loss: New Insights for the Clinician," *Therapeutic Advances in Musculoskeletal Disease* 4, no. 2 (April 2012): 61–76, https://doi.org/10.1177/1759720X11430858.

79 American Family Physician, "What Causes Falls in the Elderly?"

80 Ken E Evans, "Auxetic Polymers: A New Range of Materials," *Endeavour* 15, no. 4 (January 1991): 170–74, https://doi.org/10.1016/0160-9327(91)90123-S; Yanping Liu and Hong Hu, "A Review on Auxetic Structures and Polymeric Materials," *Scientific Research and Essays* 5 (May 18, 2010): 1052–63.

81 Wangyu Liu et al., "In-Plane Dynamic Crushing of Re-Entrant Auxetic Cellular Structure," *Materials & Design* 100 (June 2016): 84–91, https://doi.org/10.1016/j.matdes.2016.03.086.

82 Evans, “Auxetic Polymers.”

83 Ibid.

84 Ibid.

85 Krishna Kumar Saxena, Raj Das, and Emilio P. Calius, “Three Decades of Auxetics Research – Materials with Negative Poisson’s Ratio: A Review: Three Decades of Auxetics Research…,” *Advanced Engineering Materials* 18, no. 11 (November 2016): 1847–70, https://doi.org/10.1002/adem.201600053.

86 Ibid.

87 Ibid.

88 Yannis Dionyssiotis, “Analyzing the Problem of Falls among Older People,” *International Journal of General Medicine*, September 2012, 805, https://doi.org/10.2147/IJGM.S32651.

89 L. J. Gibson et al., “The Mechanics of Two-Dimensional Cellular Materials,” *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 382, no. 1782 (1982): 25–42; Jinhee Lee, J. B. Choi, and K. Choi, “Application of Homogenization FEM Analysis to Regular and Re-Entrant Honeycomb Structures,” *Journal of Materials Science* 31, no. 15 (August 1996): 4105–10, https://doi.org/10.1007/BF00352675.

90 Yuanlong Wang et al., “Optimization of an Auxetic Jounce Bumper Based on Gaussian Process Metamodel and Series Hybrid GA-SQP Algorithm,” Structural and Multidisciplinary Optimization 57, no. 6 (June 2018): 2515–25, https://doi.org/10.1007/s00158-017-1869-z; Yuanlong Wang et al., “Parametric Analysis of a Cylindrical Negative Poisson’s Ratio Structure,” Smart Materials and Structures 25, no. 3 (February 22, 2016): 035038, https://doi.org/10.1088/0964-1726/25/3/035038; Qiang Gao et al., “Theoretical, Numerical and Experimental Analysis of Three-Dimensional Double-V Honeycomb,” Materials & Design 139 (February 2018): 380–91, https://doi.org/10.1016/j.matdes.2017.11.024; Yuanlong Wang et al., “A Negative Poisson’s Ratio Suspension Jounce Bumper,” Materials & Design 103 (August 2016): 90–99, https://doi.org/10.1016/j.matdes.2016.04.041.

91 Yong Xu et al., “Penetration Depth and Nonlocal Manipulation of Quantum Spin Hall Edge States in Chiral Honeycomb Nanoribbons,” *Scientific Reports* 7, no. 1 (December 2017): 7578, https://doi.org/10.1038/s41598-017-07994-z; Ming-Hui Fu, Bin-Bin Zheng, and Wei-Hua Li, “A Novel Chiral Three-Dimensional Material with Negative Poisson’s Ratio and the Equivalent Elastic Parameters,” *Composite Structures* 176 (September 2017): 442–48, https://doi.org/10.1016/j.compstruct.2017.05.027.

92 Yoshihiro Ishibashi and Makoto Iwata, “A Microscopic Model of a Negative Poisson’s Ratio in Some Crystals,” *Journal of the Physical Society of Japan* 69, no. 8 (August 15, 2000): 2702–3, https://doi.org/10.1143/JPSJ.69.2702; A.A. Vasiliev, S.V. Dmitriev, and A.E. Miroshnichenko, “Multi-Field Approach in Mechanics of Structural Solids,” *International Journal of Solids and Structures* 47, no. 3–4 (February 2010): 510–25, https://doi.org/10.1016/j.ijsolstr.2009.10.016; J. N. Grima and K. E. Evans, “Auxetic Behavior from Rotating Squares,” *Journal of Materials Science Letters* 19, no. 17 (2000): 1563–65, https://doi.org/10.1023/A:1006781224002.

93 R. S. Lakes, “Design Considerations for Materials with Negative Poisson’s Ratios,” *Journal of Mechanical Design* 115, no. 4 (December 1, 1993): 696–700, https://doi.org/10.1115/1.2919256; Shu Yang et al., “Energy Absorption of an Re-Entrant Honeycombs with Negative Poisson’s Ratio,” *Applied Mechanics and Materials* 148–149 (December 2011): 992–95, https://doi.org/10.4028/www.scientific.net/AMM.148-149.992.

94 Juan Carlos Álvarez Elipe and Andrés Díaz Lantada, “Comparative Study of Auxetic Geometries by Means of Computer-Aided Design and Engineering,” Smart Materials and Structures 21, no. 10 (July 2012): 105004, https://doi.org/10.1088/0964-1726/21/10/105004.

95 Yoshikazu Shinohara, “Functionally Graded Materials,” in *Handbook of Advanced Ceramics* (Elsevier, 2013), 1179–87, https://doi.org/10.1016/B978-0-12-385469-8.00061-7.

96 FormLabs, “Choosing the Right Material,” accessed July 30, 2020, https://support.formlabs.com/s/article/Choosing-the-Right-Material?language=en_US.

97 Oxman, “Material-Based Design Computation.”

98 Lavender Tessmer et al., “Active Textile Tailoring,” in *ACM SIGGRAPH 2019 Emerging Technologies* (SIGGRAPH ’19: Special Interest Group on Computer Graphics and Interactive Techniques Conference, Los Angeles California: ACM, 2019), 1–2, https://doi.org/10.1145/3305367.3327995.

99 Yang et al., “Energy Absorption of an Re-Entrant Honeycombs with Negative Poisson’s Ratio”; Tao Wang et al., “Dynamic Crushing Analysis of a Three-Dimensional Re-Entrant Auxetic Cellular Structure,” *Materials* 12, no. 3 (February 1, 2019): 460, https://doi.org/10.3390/ma12030460.

100 Gunvor Gard and Glenn Berggård, “Assessment of Anti-Slip Devices from Healthy Individuals in Different Ages Walking on Slippery Surfaces,” *Applied Ergonomics* 37, no. 2 (March 2006): 177–86, https://doi.org/10.1016/j.apergo.2005.04.004.

101 Kluwer Health : Lippincott Williams & Wilkins Wolters, “Color Vision Problems Become More Common with Age, Study Shows,” ScienceDaily, accessed July 25, 2020, https://www.sciencedaily.com/releases/2014/02/140220102614.htm.

102 Stephen Downs, Jodie Marquez, and Pauline Chiarelli, “Normative Scores on the Berg Balance Scale Decline after Age 70 Years in Healthy Community-Dwelling People: A Systematic Review,” *Journal of Physiotherapy* 60, no. 2 (June 2014): 85–89, https://doi.org/10.1016/j.jphys.2014.01.002.

103 Tony Rosen, Karin A. Mack, and Rita K. Noonan, “Slipping and Tripping: Fall Injuries in Adults Associated with Rugs and Carpets,” *Journal of Injury and Violence Research* 5, no. 1 (January 1, 2013): 61–65, https://doi.org/10.5249/jivr.v5i1.177.

104 Olga I. Vinogradova, “Slippage of Water over Hydrophobic Surfaces,” *International Journal of Mineral Processing* 56, no. 1–4 (April 1999): 31–60, https://doi.org/10.1016/S0301-7516(98)00041-6.

105 Kyriacos Kareklas, Daniel Nettle, and Tom V. Smulders, “Water-Induced Finger Wrinkles Improve Handling of Wet Objects,” *Biology Letters* 9, no. 2 (April 23, 2013): 20120999, https://doi.org/10.1098/rsbl.2012.0999.

106 J. M. Dinwoodie, *Timber, Its Nature and Behavior*, 2nd ed (London ; New York : [England]: E & FN Spon ; BRE, with the support of the Centre for Timber Technology and Construction at BRE, 2000).

107 Tomlinson et al., “Human Finger Friction in Contacts with Ridged Surfaces.”

108 Ibid.

109 Wolters, “Color Vision Problems Become More Common with Age, Study Shows.”

110 Ibid.

111 Paul Arthur and Romedi Passini, *Wayfinding: People, Signs, and Architecture*, Repr (Oakville, Ont: Focus Strategic Communications Inc, 2002).

112 Ibid.

113 Blatteis, "Age-Dependent Changes in Temperature Regulation - a Mini Review."

114 Ibid.

115 Ibid.

116 Reichert, Menges, and Correa, "Meteorosensitive Architecture."

117 Ibid.

118 David Correa et al., "HygroSkin: A Prototype Project for the Development of a Constructional and Climate Responsive Architectural System Based on the Elastic and Hygroscopic Properties of Wood" (ACADIA 13: Adaptive Architecture [Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture, Cambridge, Ontario, 2013), 33–42.

119 "Relative Humidity - Monthly Data for Toronto," Amateur Weather Statistics for Toronto, Ontario, accessed July 30, 2020, https://toronto.weatherstats.ca/charts/relative_humidity-monthly.html.

120 Reichert, Menges, and Correa, "Meteorosensitive Architecture."

121 Elena Vazquez, Benay Gürsoy, and Jose Pinto Duarte, "Formalizing Shape-Change: Three-Dimensional Printed Shapes and Hygroscopic Material Transformations," International Journal of Architectural Computing 18, no. 1 (March 2020): 67–83, https://doi.org/10.1177/1478077119895216.

122 Nicola Augustin and David Correa Zuluaga, *Developing Climate-Responsive Envelopes with the Hygroscopic Motion of Wood Veneer*, 2019.

123 Sherif Abdelmohsen and Rana El-Dabaa, *HMTM: Hygromorphic-Thermobimetal Composites as a Novel Approach to Enhance Passive Actuation of Adaptive Façades*, 2019.

Appendix A

Auxetic Apparel Material Range of Motion Visualization

This appendix is a video file showcasing the range of motion the auxetic material of design experiment 1 : Auxetic Apparel. The file name of this video file is, "Auxetic Apparel_motion range.mp4". The video is made by the author of this thesis and is subject to copyright.

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Appendix B

Hydrofloor Motion Visualization

This appendix is a video file showcasing the changing states (dry to wet) of design experiment 2 : Hydrofloor proof of concept prototype. The file name of this video file is, “Hydrofloor_dry to wet.mp4”. The video is made by the author of this thesis and is subject to copyright.

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Appendix C

Breathing Facade Motion Visualization Prototype 1

This appendix is a video file showcasing the autonomous aperture system of design experiment 3 : Breathing facade prototype 1. The file name of this video file is, “BreathingFacade_prototype 1.mp4”. The video is made by the author of this thesis and is subject to copyright.

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Appendix D

Breathing Facade Motion Visualization Prototype 2

This appendix is a video file showcasing the autonomous aperture system of design experiment 3 : Breathing facade prototype 2. The file name of this video file is, “BreathingFacade_prototype 2.mp4”. The video is made by the author of this thesis and is subject to copyright.

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Appendix E

Breathing Facade Motion Visualization Prototype 3

This appendix is a video file showcasing the autonomous aperture system of design experiment 3 : Breathing facade prototype 3. The file name of this video file is, "BreathingFacade_prototype 3.mp4". The video is made by the author of this thesis and is subject to copyright.

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