Living Therapeutic Skin (LTS): Design Opportunities and Challenges of On-Skin Living Artefacts

Raphael Kim[1,2(✉)], Fanzhe Zeng[1], Tom Ellis[3], and Elvin Karana[1]

[1] Delft University of Technology, Delft, The Netherlands
raphael@biodesign.academy, {F.Z.Zeng,E.Karana}@tudelft.nl
[2] Biodesign Academy, London, England
[3] Imperial College London, London, England
t.ellis@imperial.ac.uk

Abstract. The Living Therapeutic Skin (LTS) is a novel living material currently in development as part of a European project. Integrating engineered microbes to detect and treat eczema flare-ups, LTS offers significant promise for managing this prevalent skin condition. However, as a microbial material in its early developmental stage, LTS faces challenges related to social acceptance when it is embedded in on-skin living artefact for daily human use. To address these challenges in the further development of these materials, we conducted a workshop employing boundary objects to illustrate four hypothetical LTS applications in everyday contexts. Our participatory approach engaged a multidisciplinary group, including a dermatologist, scientists, biodesigners, and eczema patients. Analysis of the workshop data revealed several important factors affecting the wearability and acceptance of on-skin living artefacts. This paper elaborates on these factors to explore the potential implications of LTS, examining its design prospects and hurdles while discussing possible avenues for a broader range of human-skin interfaces.

Keywords: On-skin living artefacts · Boundary objects · Workshop

1 Introduction

The Living Therapeutic Skin (LTS) is a microbial living material that is envisioned as a wearable artefact for the dynamic and responsive treatment of skin-based disorders (NextSkins 2023). It is composed of a bacterial cellulose hydrogel housing responsive yeast cells. Through synthetic biology and protein engineering methods (e.g., Ng et al. 2020; Gilbert et al. 2021), this therapeutic skin is intended to be designed into three layers: an interactive layer with sensory and response functions, a core layer housing living cells, and a barrier layer for containment and hydration. LTS is proposed to be engineered to detect clusters of Staphylococcus aureus bacteria during Atopic Dermatitis (eczema) flare-ups and releases compounds inhibiting bacterial growth. LTS design team follows a multidisciplinary and collaborative material development approach (Karana

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et al. 2015; Barati and Karana 2019) to design the living material as a form of living artefact for human interaction in the everyday context (Karana et al. 2020). In its use, it is envisioned to provide cues to users concerning its active state or indicating the severity of the skin condition. Yet, as this innovative material integrates living components which are meant to be on human-skin, tensions arise concerning user experience and societal acceptance, as well as managing the end-of-life phase of these wearable designs (e.g., Lu & Lopes 2018; Jones & Brown 2019).

Understanding the user experience of LTS, a semi-developed material, presents significant challenges. Firstly, similar to other collaborative material development projects with semi-developed samples (Barati et al. 2019), LTS is not yet accessible for physical engagement due to its unfinished state. This limitation restricts eLective communication and collaboration between material and biological scientists, designers, and other crucial stakeholders such as medical experts and potential end-users. Secondly, even with more advanced samples, living materials require strict safety protocols for handling within collaborative design groups, making it diLicult to present them to potential end-users. To address these challenges and obtain feedback in the early development stages, we propose a workshop utilising diverse boundary objects (Star & Griesemer 1989), designed by our multidisciplinary living material development team.

To comprehensively delve into the multifaceted implications of LTS, we organised a workshop with stakeholders including a dermatologist, scientists, biodesigners, and eczema patients. Our LTS boundary objects portrayed four carefully designed hypothetical scenarios and their corresponding conceptual living artefacts showcasing potential LTS applications in everyday life. The participatory approach aimed to foster interactive discussions and vision expansion. Our analysis conducted on the rich dataset extracted from the workshop revealed several pivotal emergent themes, including aspects like material experience (Giaccardi & Karana 2015), ethical implications of integrating living components into wearables, technological feasibility, and overall social acceptance (Brown & Miller 2018). These themes serve as a foundational basis for exploring the wide-ranging implications of LTS within the design and Human-computer Interaction (HCI) community, particularly in the realm of on-skin interface designs.

2 Related Works

2.1 On-Skin Interfaces in Design

On-Skin Interfaces refer to technologies designed to be worn directly on the body, specially designed to adhere directly to the human skin, enabling seamless interaction between humans and computers (e.g., Ogata et al. 2013; Restrepo-Villamizar et al. 2021). These interfaces leverage advancements in materials, sensors, and miniaturized electronics to create unobtrusive, convenient, and often biometrically sensitive devices. Current on-skin interfaces designs exhibit a wide range of interaction patterns, for example, input modalities such as touching (e.g., Weigel et al. 2015; Kao et al. 2016), biometric data (e.g., Kao et al. 2016; Dong et al. 2022), body fluids (e.g., Reeder et al. 2019; Ikeda et al. 2022), and environmental factors like chemicals (e.g., Kao et al. 2017), and output modalities, for instance, morph and colour changes (e.g., Kao et al. 2017; Weigel at el. 2017), olfactory (e.g., Wang et al. 2020), and facial expressions (e.g., Wang et al. 2022).

However, keeping the balance between functionality and compactness of on-skin interfaces has always been a challenge; the pursuit of more complex functions often necessitates larger and heavier electronics, components, and power supplies—a juxtaposition that conflicts with the desirable minimal size and weight of these interfaces. Multiple efforts have been addressed to tackle this challenge, encompassing the invention of new and miniature components (e.g., Dementyev 2015; Wang et al. 2020), the development of novel materials serving as sensors and actuators (e.g., Kao et al. 2017; Kao et al. 2018), and more.

In acknowledging the multifaceted factors influencing the wearability of on-skin interfaces and recognizing the distinct design challenges and opportunities they present, Liu et al. (2016) have compiled a guideline. This guideline serves as a compass for designers, enabling them to efficiently navigate the myriad considerations when developing their own iterations of on-skin interfaces. Liu's exploration encompassed an in-depth analysis of wearability factors encompassing both the physiological aspects (such as location, movements, and individual body traits) and technical elements (such as covering weight, attachment methods, accessibility, interaction interfaces and aesthetics). This holistic approach provides a roadmap for designers seeking to strike the delicate balance between functionality and minimalism in the realm of on-skin interfaces.

2.2 On-Skin Biomaterials

The concept of biomaterials, usually defined as synthetic or natural substances capable of interacting with living systems (Achermann et al. 2014), has a long history dating back to traditional healing practices. Seaweed, for instance, has been used as a wound dressing for centuries by various indigenous cultures (Thurstan et al. 2018). Similarly, herbal remedies have been employed in both oral and topical forms for millennia in many countries across the world (Halberstein 2005). With the advancement of science and technology, microorganisms, once considered invisible and intractable, have become increasingly valuable for biomaterial development (Rodrigo-Navarro et al. 2021). The healthcare sector stands to benefit from the remarkable characteristics of lab-grown biomaterials, particularly their non-toxicity, biocompatibility, and biodegradability properties (Wang 2023). Specifically, bacterial cellulose, produced by bacteria and yeasts, emerge as a promising material for wound dressing, drug delivery, and tissue engineering due to its low cytotoxicity, excellent biocompatibility, and ability to foster cell growth and tissue formation (Cacicedo et al. 2020; Han et al. 2020).

In parallel, within the context of biological-HCI (Pataranutaporn et al. 2018), wearable biomaterials are beginning to be considered computational materials for human-microbe interactions. Among these advancements, an innovative and intriguing realm emerged recently; using computationally engineered microbes (also called living bits (Pataranutaporn et al. 2020) as interacting material or computers (Pataranutaporn et al. 2018) in on-skin interfaces. For example, the Living Tattoo Project involves printing engineered cells on a bilayer elastomeric sheet. These cells can sense and respond to chemicals on the user's skin, displaying their reactions through fluorescence and acting as a skin health monitor (Liu et al. 2018). These living interfaces, harnessing the intelligence and adaptability of the living microbes, are self-contained systems that offer dynamic and responsive user experiences without the need for electronics or external power. Moreover, livingness, as a surfaceable design quality (Karana et al. 2020; Kim et al. 2023), also fosters unconventional interactive and aesthetic engagement with wearers, potentially promoting an understanding and appreciation of microbes' diverse needs, scales, agencies, and temporalities, thereby encouraging practices of care and bridging the cognitive gap that has long separated humans from nature (Karana et al. 2023).

Moving forward, in this paper, we delve deeper into the realm of biological-HCI, where our focus shifts towards exploring living therapeutic skin as a nascent but promising wearable biomaterial. By harnessing existing wearability factor guidelines, we aim to delineate a distinct set of design opportunities and challenges inherent to Living Therapeutic Skin (LTS).

2.3 Exploration of LTS Through Boundary Objects

Boundary objects serve as common reference and knowledge points for various stakeholders in collaborative settings (Star & Griesemer 1989). These objects can take multiple forms, depending on objectives of the design process (e.g., Halpern 2012; Zimmermann & Pluchinotta 2020). They may be tangible artefacts, such as assembly drawings that facilitate knowledge exchange between manufacturing and design engineers (Carlile 2002), heritage products embodying perspectives of both craftspeople and designers (Suib et al. 2020), or machines that bridge understanding among managers, engineers, and assemblers (Bechky 2003). Boundary objects can also be more abstract, such as design methods, narratives, or metaphors (Koskinen 2005; Enninga & van der Lugt 2016). For instance, in designing a digital healthcare platform, patient stories can serve as open boundary objects and design goals as metaphorical semi-open boundary objects (Islind et al. 2019). More recently, boundary objects can also encompass artefacts that integrate living organisms and processes (Ramirez-Figueroa 2018).

The LTS project, as a biodesign endeavour (Myers 2012), involves stakeholders such as scientists, designers, medical experts, patients, and microorganisms. Current challenges stem from the semi-final development stage of LTS and safety considerations of genetically engineered organisms, restricting LTS to laboratory settings. This creates a knowledge and experiential gap between scientists developing the material and downstream stakeholders like medical experts and users. Furthermore, both the knowledge boundary and the physical boundary (the laboratory door) contribute to a separation between the novel living material and the everyday practicalities. Speculative scenarios have proven effective and provocative in design workshops for linking novel technology and design to reality (e.g., Huusko & Roto 2018; Nygrén 2019). Thus, we adopted speculative scenarios as boundary objects to bridge the gap between LTS and daily life, fostering critical discussions on LTS in various contexts. Through carefully designing and crafting LTS boundary objects, our objective is not only to align all involved actors, but also facilitating real-life engagement with LTS beyond laboratory settings, fostering a more intimate, experiential and inclusive participation for all.

3 Methodology

To explore the diverse perspectives on Living Therapeutic Skin (LTS), we designed and organised a workshop that brought together 15 stakeholders from various backgrounds, including a dermatologist, ten scientists, two biodesigners, and two Eczema patients, who were affiliated with the research project. The workshop spanned approximately 3 h. Four speculative scenarios and their corresponding artefacts have been designed, visualised and prototyped to explore various potentials of LTS and transform them into comprehensible narratives.

3.1 Context of Use: Eczema

Eczema, or atopic dermatitis, is a chronic inflammatory skin disease marked by persistent itching and eczematous lesions (McNally & Phillips 2000). It affects around 20% of children and 5% of adults globally (Asher et al. 2006). Patients experience intense itching, sleep disturbances, reduced productivity, and social challenges, along with anxiety, depression, and frustration (Simpson et al. 2016). The disease fluctuates between flare-ups and remissions, with periods of worsening followed by relative control (Girolomoni & Busà 2022). There is a noted correlation between the severity of flares and increased colonization of Staphylococcus aureus (S. aureus) on the skin (Girolomoni & Busà 2022). Therapeutic LTS materials are used during flares to detect S. aureus and release molecules that inhibit its growth. Eczema impacts both physical and psychological well-being. Treatments include topical medications, oral drugs like Methotrexate, and phototherapy (Ross 2023). Psychological therapies, such as muscle relaxation, social competence training, and hypnotherapy, have also improved patient quality of life (Ersser et al. 2014).

3.2 Designing the LTS Boundary Objects

When designing the Living Therapeutic Skin (LTS), we integrated the initial material development directions provided by Tom Ellis Group at Imperial College London—such as potential thickness, transparency, and colour indications—with the psychological implications of eczema. For the latter, we placed special emphasis on crafting the material's texture to enhance the experiential qualities of LTS, focusing on three key aspects: (1) the material should exhibit vitality and naturalness, highlighting the living quality of LTS; (2) it should convey a sense of healing, reflecting the therapeutic nature of LTS; and (3) it should foster meditative interactions between patients and the textural interface, aiming to alleviate negative emotions associated with eczema flares. To guide our design process, we drew inspiration from textures in nature, clustering them into three pairs: Water Ripple and Wave Textures: Inspired by the dynamic aesthetics of water, these textures aim to make users feel calm and relieved; Shell and Scale Textures: Designed to resemble the protective layers of critters, these textures convey meanings of protection, security, and intimacy; Tentacle and Fin Textures: These exhibit more interactive qualities, prompting actions such as caressing, sliding, and squeezing to evoke calmness and relaxation during use (Fig. 1).

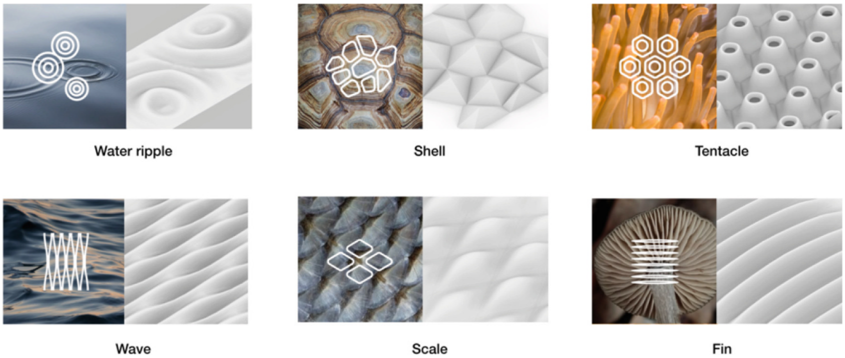
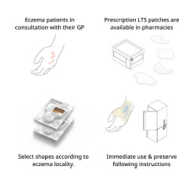
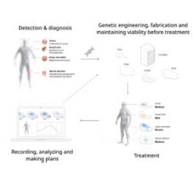
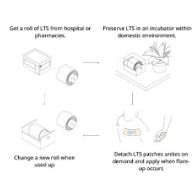


Fig. 1. Directions for LTS texture design

3.3 Design Scenarios and the Corresponding Artefacts

Based on the analysis of the eczema context and the initial development of LTS within the NextSkins project consortium, we created four scenarios that integrate the technology, design potentials, and daily narratives related to eczema. In the first scenario, named "daily patches", we delve into the ease of use and convenience aspects of LTS. LTS patches serve as ready-to-use products in pharmacies. The second scenario, situated in skin "therapy centres", addresses the possibilities of highly customised and responsive skin therapy through LTS. In "domestic integration", we shift the focus to the care practices of LTS as a daily routine. Finally, the "implantation" scenario speculates on the future extension of the technology- implanting LTS underneath the skin as a permanent treatment. Table 1 shows a summary of each scenario, and the accompanying illustrations.

Table 1. LTS scenarios developed for the workshop with diverse stakeholders.

Scenarios	**Scenario A** **Daily patches**	**Scenario B** **Therapy Centers**	**Scenario C** **Domestic Integration**	**Scenario C** **Implantation**
Descriptions	LTS patches could serve as prescription remedy for AD patients, usable for immediate relief or preventive purposes. Following General Practitioners (GP)'s prescription, patients are able to collect them in pharmacies. LTS patches will come with various shapes tailored to fit different affected areas of the patients' body. Patients will be informed how to store the patches and the viability of the LTS through instructions on the package.	LTS patches could be used in skin therapy centres for eczema patients. These centres store and maintain the patches in highly controlled settings, maintaining their viability. They also track patients' progress by recording the microbial interface during visits, aiding in future treatments. Additionally, these patches can be tailored to individual needs by analyzing customers' skin microbiome composition. This customization enhances their effectiveness, providing targeted care based on unique skin requirements.	Design Vision with the scenario is to integrate LTS material seamlessly into eczema patients' domestic life, offering not only effective treatment for patients' symptoms, but also for the LTS's care during its dormant states, at home. The design concept shapes the LTS material like a roll, making it familiar and user-friendly, allowing customization for optimal coverage. It includes a domestic incubator to maintain LTS material viability during dormant periods, ensuring it's ready for use.	Eczema is a long-lasting skin condition, especially severe cases require ongoing treatment. There may be a development of an option for patients to use implants, that would embed LTS-like patches under the skin, for continuous therapy. LTS patches use living microbes and thrive by using the body's temperature and moisture, functioning like "secondary organ" under the skin, to sense and treat eczema without electronic and/or manual intervention.
Illustration				

These scenarios and their visuals are implemented into the workshop as boundary objects. Although we use the term "speculative", these scenarios are situated in familiar contexts including pharmacy, therapy centres, home and hospital, which creates common vessels, within which participants from various communities will have different experiences as internal contents (Star & Griesemer 1989). For instance, medical experts who prescribe LTS and patients accepting LTS might have different experiences, perspectives and concerns in a therapy centre or hospital contexts, and scientists and designers might have different visions for the future development of LTS.

Apart from the graphic representations of four scenarios, we also designed and prototyped tangible artefacts following the central concepts embodied in the four scenarios (Fig. 2), aiming to establish an experiential, sensory relationship with the speculative scenarios for all workshop participants (Coughlan et al. 2007). We used bio-silicone in the design of our tangible boundary objects due to its close resemblance to the LTS (revealed in informal discussions with the scientists within NextSkins) in terms of sensorial and performative qualities (Karana et al. 2015). It is a safe material for physical engagement. Moulds, crafted through 3D printing and Lego bricks, were employed to shape the LTS objects and engrave nature- inspired textures as mentioned in the previous part.

For the Daily Patches scenario, alternative LTS samples with textures were crafted into ergonomic shapes tailored to different body sites, enabling participants to wear them and intimately experience the material (2, A). In the Domestic Integration scenario, we shape the material into long-stripe form and wound it around the knob of an incubator, inviting participants to test the convenience of the using and caring interaction (2, B). For the Therapy Centers scenario, a digital-physical simulation was implemented. The temporal changes in the responsive interface facilitated by microbes, which is designed to reflect users' real-time skin condition, were simulated through animation. An iPad was used to play the animation with a piece of material sample on top of the screen, creating the illusion of microbial responses being directly displayed on the material's surface (2, C). In the Implantation scenario, digital simulations were predominantly employed to render the temporal changes of the interface beneath the skin (2, D).

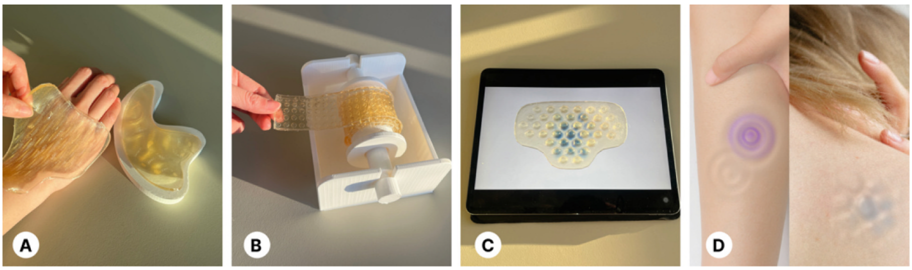


Fig. 2. LTS tangible boundary objects.

4 Workshop

The workshop consists of three main parts. Firstly, the workshop kicked off with a short joint presentation by the first and second authors, outlining the main aims behind the session and introducing the LTS technology. The workshop was then divided into two parts, namely ice-breaker activity and scenarios exploration.

4.1 Ice-Breaker Activity

The main aim of the activity was to assess how participants perceived LTS technology in treating eczema. This involved considering key factors such as its efficacy, comfort, ease of use, safety, and environmental impact. Participants collaborated in groups of 3 or 4 and were tasked with rating LTS based on these five aspects, using a 7-point Likert scale provided in a worksheet. For instance, under the efficacy section, the worksheet prompted them to answer the question, "How do you perceive LTS in terms of its efficacy?" ranging from -3 (not very effective) to $+3$ (very effective), and similar questions were posed for the other factors. Each question on the worksheet included a box below the scale, allowing participants to briefly explain their rating decisions. Overall, this exercise aimed to engage participants and set the stage for subsequent activities, fostering a more receptive atmosphere among the participants.

4.2 Scenario Explorations

Here, we have delved further into the potential applications of LTS through four scenarios and related tangible artefacts. Following the presentations of the scenarios, working in the same assigned group, the participants were asked to assess each scenario, using a 7-point Likert scale provided on separate worksheets. This time, there were four criteria with which their responses were recorded: Plausibility of the scenario to occur within 5 years; Plausibility of the scenario to occur within 10 years; Social acceptance; and Ease of application. In addition to the ratings, a separate box was provided in the worksheet for the participants to briefly elaborate on the scenarios, highlighting the potential challenges and opportunities they would bring to the stakeholders of the technology. Note that these scales were not intended to identify significant discrepancies or agreements among participants, but rather to support and inspire our qualitative assessment. Following that, each scenario was individually assessed and discussed in a group discussion (Fig. 3).

Following the activities, all data were collected and analysed by the lead and co-authors. From the analysis, we distilled a series of design opportunities and challenges. These intricacies are rooted in various wearability factors and form the focal point of our inquiry into the potential implications of LTS.

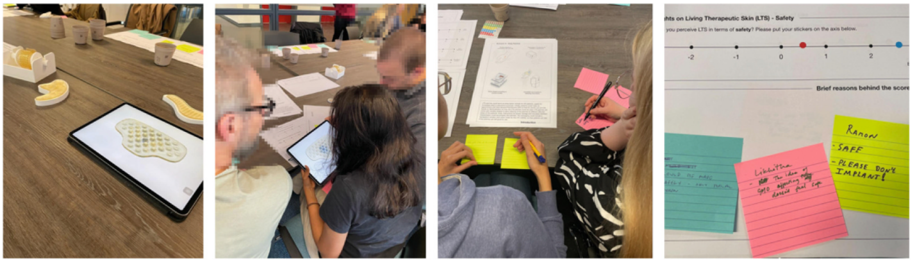


Fig. 3. Workshop activities: participants exploring boundary objects and completing worksheets

5 Findings

5.1 General Assessment of LTS Technology

Here, we offer a summarised representation of the Likert scale findings regarding the five factors (Fig. 4). These visuals aim to encapsulate participants' views on each factor. Additionally, we outline concise explanations of the findings, capturing the general sentiment associated with each factor. To enhance comprehension, we occasionally include direct quotes from participants to illustrate our points.

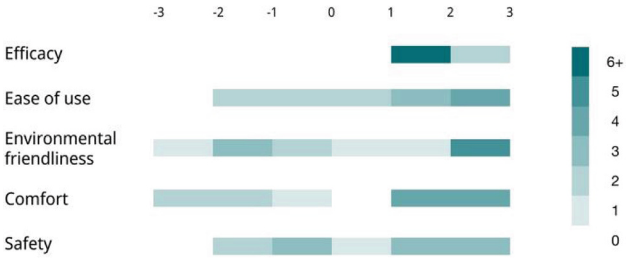


Fig. 4. Perceptions of LTS

Efficacy

Most participants generally regard the LTS artefact as relatively effective, with some expressing it as better than existing treatments. However, concerns were raised regarding its *temporal behaviour*, particularly about the speed at which the LTS artefact would function or its promptness in treating the affected skin areas—given its microbial interactions, many participants speculated that it might take a while to produce noticeable effects. Moreover, the complexity of different elements might influence sensing or the therapeutic response, posing another challenge. The efficacy was also questioned in terms of scale, as the human skin covering the entire body presents a significantly larger surface area than the LTS patch, potentially limiting direct contact and interaction. Nonetheless, there were positive perspectives expressed as well, some participants believed the patch might offer a cooling and calming effect.

Ease of Use

Regarding the ease of use of LTS, the majority of participants perceived it to be relatively straightforward. They mentioned that the artefact seemed intuitive to use, describing it as a "stick and go" concept or using phrases like "easy as 1,2,3." However, a smaller subset of participants didn't find it easy to use. They expressed concerns that using LTS would necessitate *proactive care practices* to maintain the artefact.

Environmental friendliness

The majority of participants viewed the LTS material as relatively environmentally friendly. Their reasoning stemmed from being informed that the material was crafted from renewable compounds and organic substances. Additionally, some participants were aware that it was designed to be biodegradable and manufactured with reduced dependence on fossil energy. However, a minor concern surfaced when one participant found it challenging to envision the optimal *end-of life* scenarios for the LTS material. Despite this, the overall consensus leaned towards perceiving LTS as a product aligned with "green chemistry," fostering sustainability.

Comfort

Participants had diverse opinions regarding the comfort of the LTS. Some found it to be relatively comfortable and expressed positive remarks, highlighting the pleasant *tactile experience* it provided. They mentioned feeling a nice sensation akin to a "cold patch and cloth," preferring it over the sensation of a band-aid. They also appreciated its potential cooling effect, attributing it to its non-dry nature and the presence of hyaluronic acid. Conversely, those who didn't find LTS comfortable cited several reasons. They believed that the design of LTS might compromise comfort, potentially limiting movement and causing it to fall oL when sweating. Additionally, there were concerns about potential unpleasant odours arising from the microbial makeup of the material.

Safety

As for safety, a portion of the participant cohort expressed minor doubts about the safety of *using genetically modified organisms* (GMOs). They felt uncertain about the idea and were hesitant as it didn't seem entirely safe. Additionally, some participants raised concerns about the suitability and safety of LTS for use on open skin or wounds. They highlighted the potential risk of microbes entering the skin, suggesting it might pose a safety issue, despite this being the intended working principle of the LTS material.

5.2 LTS Application Scenarios

We used the same method to visualise data from the workshop for the four scenarios (Fig. 5). Participants praised the *Daily Patch* for its convenience, home storage, and travel-friendliness. It was likened to a reassuring, easy-to-use bandage. A dermatologist noted its *effectiveness* for mild to moderate eczema in skin folds during flares. However, participants raised concerns about potential allergic reactions from repeated use, the environmental impact of single-use packaging, and the delay between prescription and relief. They also mentioned the inconvenience of frequent pharmacy visits and the wastefulness of non-reusable patches. While not widely expected in the next five years, most participants felt daily patches could gain traction within a decade due to their high social acceptance and ease of use.

Noteworthy opportunities identified include the prospect of receiving treatment from *specialised therapy centres*, allowing for fine-tuned and personalised approaches tailored to individual patients. A dermatologist participant emphasised the suitability of such treatments for individuals with severe eczema. Furthermore, one participant highlighted the social aspect, emphasising the increased potential for meaningful human interactions, providing a more personal *engagement experience*. However, drawbacks include the time-consuming nature of booking and visiting centers, along with significant costs that may hinder widespread adoption. Most participants felt therapy centres were unlikely to become widespread within five years but slightly more likely within a decade. They received high ratings for social acceptance and ease of application due to controlled, expert-assisted indoor treatments.

In the *Domestic Integration* scenario, the opportunities are quite practical, offering an in-house solution. This setup presents the chance for patients to establish a stable ritual or routine, adding a potentially enjoyable aspect to their treatment experience. Moreover, it opens up the opportunity to consider the *care of other- than-human entities* - the microbes integral to the therapy material. However, potential drawbacks exist including the risk of overuse, incorrect usage, or improper storage by patients, necessitating detailed guidelines or instructions. Managing these aspects could be perceived as an additional hassle on top of the primary goal of treating the disease. Regarding the domestic integration of LTS and its perception, the majority of participants expressed a belief that its plausibility in everyday life was fairly high, both in the next five years and the subsequent decade.

No substantial opportunities or advantages were identified regarding the *Implantation* scenario, as participants expressed strong criticism of this scenario. They deemed it highly unfeasible in the near future and considered it more as a long-term solution for eczema. While the idea had a futuristic appeal, envisioning hybrid cyborgs and aliens, it was perceived as invasive and raised concerns about potential resistance from the patients, anaphylactic shock, negative immune reactions, and new infections. The safety and practicality of using color displays within implanted skin layers were also questioned. Overall, participants felt this scenario presented more challenges than benefits, with low plausibility in the next five to ten years and low social acceptability due to its invasive nature in treatment situations.

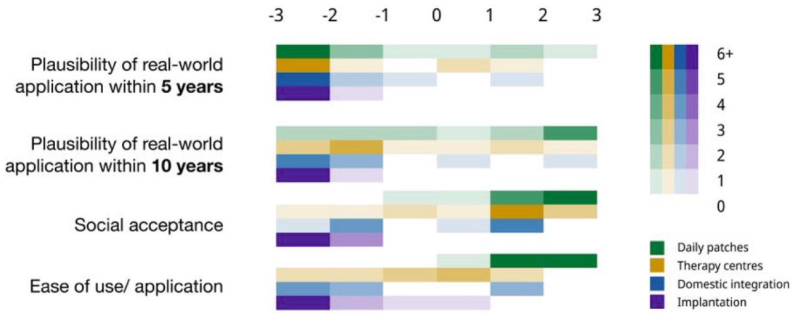


Fig. 5. Data visualisation for the scenarios

6 Discussion and Conclusions

This paper presents the findings of a workshop, focusing on Living Therapeutic Skin (LTS), exploring the potential barriers to the societal acceptance of this emerging technology, supporting its further development toward socially relevant directions. Herein, we succinctly summarise our findings, highlighting both design opportunities and challenges for LTS.

6.1 Design Opportunities

One of the most compelling opportunities for designers working with Living Therapeutic Skin (LTS) material and technology lies in starting with a *moderate, small-scale* approach, such as employing a patch format. This strategy follows the principle of introducing a novel living material through a familiar application (Karana et al. 2018). This format offers significant advantages in terms of wearability, portability, comfort, and ease of use. Notably, discussions with participating dermatologists underscore the empowering potential of daily patches for patients in managing therapies, as offering flexibility and choice is crucial in enhancing their experience. Furthermore, when examining these findings in light of the wearability factors outlined by Liu et al. (2016), it becomes evident why the daily patch stands out as the most viable and accessible application of LTS material. The biological characteristics of the material, coupled with the absence of conventional bulky electronics, make it inherently lightweight, portable, and flexible. Additionally, the daily patch format aligns with a regenerative ecology mindset (Karana et al. 2023) by utilising organic matter for an on-skin interface, which can potentially return to nature to complete its life cycle. This sustainable approach adds a crucial dimension to the design considerations of living materials.

Moreover, integrating LTS into domestic settings, including care and maintenance routines, opens up possibilities for *therapeutic care* designs that extend beyond physical treatment to encompass mental well-being. While the feasibility of such concepts in everyday situations remains untested, they present intriguing avenues for exploration. Looking ahead, the prospect of therapy centres transcends the artefact or object level, hinting at new opportunities for interaction design. This suggests a shift beyond human-to-object interaction towards more social levels, potentially paving the way for innovative designs extending beyond conventional realms of therapeutic objects.

6.2 Design Challenges

Mutualistic care has been identified as a crucial principle in designing living artefacts (Karana et al. 2020), and affection is an essential dimension of care (de La Bellacasa 2017). These affections, however, are not always positive; they can also manifest as stress, guilt, and regret upon perceiving the decline of the well- being of the living artefacts (Lu & Lopes 2018). Thus, while the emergence of an intimate bond with living artefacts holds the potential for cultivating sensibilities toward other living entities, it can also introduce complexities and challenges for users who engage with these artefacts on a daily basis (Zhou et al. 2024).

Some workshop participants articulated that constant notice and care for LTS might be engaging and intriguing, but they were also concerned this extra layer of responsibility might provoke negative feelings like worry and guilt and potentially adding to the burdens experienced by AD patients, who are already wrestling with anxiety and stress related to their sensitive skin. This juxtaposition raises critical questions: Does revealing the livingness of LTS material, aiming to form an intimate connection which is potentially able to foster a more sustainable behaviour and mend the longstanding cognitive separation of humans from nature (Karana et al. 2023), outweigh the potential burden it may impose on users, especially in a medical context? Conversely, could concealing this livingness alleviate the already heavy load on eczema patients, providing them with relief from an additional layer of responsibility? And if designers deem it necessary to surface the livingness, what approach can be adopted to establish a system that nurtures the microorganisms while simultaneously guiding users towards a more eLortless and seamless incorporation of caring practices into their daily lives? Further research is needed in the biodesign field to incorporate a broader range of perspectives from various stakeholders, making the concept of living artefacts acceptable and accessible to a wider audience.

Lastly, careful consideration is crucial when designing beyond the biological material. The LTS material is not intended to be sold or made available on its own; rather, it will be accompanied by appropriate packaging or other non-living accessories associated with the therapy. Addressing concerns raised by participants regarding the environmental impact of daily patch packaging, there is a need for a holistic view on sustainability when designing such artefacts.

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