Wearable Robotics & Facial Identity Perceptions

Graduation Project

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Abstract

This thesis explores the creation of a toolkit designed to empower artists, educators, and technologists in integrating wearable robotics into performance art, with a specific focus on transforming facial identity perception. The central research question guiding this project is: How can a comprehensive toolkit be developed to guide artists in selecting and utilizing robotic movement systems to innovatively transform facial identity perception? The toolkit, delivered as a structured website, aims to bridge the gap between artistic creativity and technical expertise, providing users with accessible resources to design and implement robotic movement systems in their artistic projects. Developed through the Creative Technology Design Process, the project combines theoretical insights, stakeholder feedback, and practical prototyping to address the diverse needs of its target audience.

The website comprises three distinct versions tailored to different user profiles: the Artistic version inspires creativity by showcasing dynamic prototypes like robotic masks and wearable tentacles, emphasizing their potential in storytelling and artistic self-expression. The Technological version provides a deep dive into the mechanics and programming of robotic systems, offering detailed tutorials, CAD files, and step-by-step guidance for technically proficient users. The Educational version focuses on beginners, presenting clear, jargon-free explanations, structured tutorials, and practical examples to demystify the complexities of wearable robotics.

Alongside the website, physical prototypes of the wearable robotics were developed and tested, including the wearable tentacle and emotion-conveying mask. These prototypes were integrated into the website to provide users with tangible examples of the technology's artistic potential and functionality.

Evaluation through semi-structured interviews and user testing highlighted the strengths and areas for improvement in each version. The Artistic version was praised for its creative inspiration but could benefit from more real-world examples. The Technological version offered robust technical depth but required simplified pathways for less experienced users. The Educational version succeeded in making wearable robotics accessible but lacked intermediate-level resources to support user progression. A key takeaway was the need for better integration between the versions, fostering seamless transitions and a cohesive learning experience.

The thesis also addresses the societal and ethical dimensions of wearable robotics, emphasizing sustainability, cultural sensitivity, and inclusivity. By incorporating open-source principles, low-power electronics, and accessible materials, the project promotes responsible innovation. The toolkit's commitment to democratizing access to wearable robotics positions it as a valuable resource for fostering interdisciplinary collaboration and advancing the intersection of art and technology.

In conclusion, this project demonstrates how a comprehensive, web-based toolkit can empower artists and other users to harness wearable robotics for innovative artistic expression. A recommendation for future work includes refining the integration of its versions, enhancing interactivity, and expanding resources to better support intermediate-level users. Additionally, the toolkit can be expanded to include more real-world applications, further strengthening the link between technology and artistic practice. With these improvements, the toolkit has the potential to become a cornerstone in wearable robotics for performance art, bridging the divide between creativity and technical expertise while promoting ethical and sustainable practices.

Table of Figures

Table of Tables

Table of Contents

1. Introduction

1.1 Context

In the age of rapid technological advances, the convergence of art, technology, and human identity has become an increasingly common theme. Historically, masks have been employed across diverse human cultures as symbolic tools to adopt or reflect alternative identities ("Masks and Human Connections," 2023). The concept of the mask, a physical entity that can transform identity, aligns profoundly with the modern possibilities offered by wearable robotics—an evolving field that seeks to create symbiotic interactions between humans and machines (Cohn & Wheeler, 2012).

While a preceding study (van der Galiën, 2023) from client Jonathan Reus explored the psychological implications of masks and their design in theatrical settings, primarily from a perceptual and design perspective, this research pivots towards the domain of wearable robotics. Continuing on a strong psychological background, this work delves into integrating lightweight wearable robotics into masks. However, the scope extends further than facial expression alone: multiple new prototypes—ranging from a wearable tentacle to a rack-and-pinion system—demonstrate various movement techniques in wearable form. These prototypes each explore different ways to infuse performance art with dynamic, interactive features that can alter or enhance identity.

The challenge of merging traditional art with sophisticated mechatronics offers a unique vantage point to re-examine our understanding of identity in a technologically driven society. By developing a comprehensive set of wearable prototypes (including masks, tentacles, four-bar linkages, and linear actuator systems), this thesis aims to provide artists with a versatile toolkit to achieve distinct forms of movement and expression in live performances.

In embracing this challenge, this thesis endeavours to bridge the gaps between design, functionality, and perception. It aligns itself with the cutting-edge developments in wearable robotics while staying attuned to mask design's artistry and cultural nuances. (Updated) Beyond the primary focus on robotic facial expression, the additional prototypes collectively illustrate how varied mechanical systems can interact with the human body, offering fluid motion, periodic movement, or experimental attachments that expand creative possibilities for performance art.

1.2 Research Questions

In the dynamic intersection of art, technology, and human identity, wearable robotics emerges as a transformative medium. This chapter delves into the pivotal questions guiding our exploration of how movement systems in robotics can be harnessed to reshape facial identity perceptions artistically—and, more broadly, how diverse prototypes can enrich performance art.

Main question: "How can a comprehensive toolkit be developed to guide artists in selecting and utilizing robotic movement systems to innovatively transform facial identity perception?"

While masks are a primary focus, additional systems (such as the wearable tentacle or four-bar linkage) will be explored for their capability to contribute novel forms of expression and motion. The emphasis remains on influencing and altering perceptions of identity or presence in artistic settings.

Subquestion 1: “What are the primary and emerging movement systems utilised in the field of robotics, and how do they differ in terms of functionality, adaptability, and efficiency?”

This question aims to identify and differentiate the main and upcoming movement systems in robotics. It seeks to understand their unique functionalities, adaptabilities, and efficiencies, laying the groundwork for their potential applications in varied wearable prototypes.

Subquestion 2: “Which movement systems are best suited for wearable applications in terms of comfort, safety, and integration with the human body?”

Here, the focus narrows down to wearable applications. The question aims to determine which movement systems align best with the requirements of comfort, safety, and seamless integration when worn on or close to the human body. Findings will help guide the choice of actuators or linkages for the tentacle, actuator-syringe system, and other solutions.

Subquestion 3: “How can wearable movement systems be innovatively applied to create artistic expressions that influence facial identity perception?”

This question delves into the artistic applications of wearable movement systems. It seeks to explore how these systems can be used creatively to craft artistic expressions that have a direct impact on how facial identities are perceived. While the robotic mask remains central to altering facial identity, the additional prototypes will showcase ways to expand expression and stage presence through fluid or rhythmic motion.

Subquestion 4: “What specific methods, mechanisms, and resources can be included in a toolkit to support artists in creating wearable robotic devices that transform facial identity perception?”

This question focuses on the practical application and prototyping of wearable robotics principles. It aims to understand how these principles can be actualized into devices that either enhance or completely transform facial identity perceptions, especially in artistic and performance settings. By detailing multiple prototypes—ranging from a mask to a wearable tentacle—the thesis aims to create a toolkit that assists artists in choosing and applying the right movement system to achieve the desired aesthetic and expressive goals.

Subquestion 5: “What is the optimal structure, content composition, and sharing method for a wearable robotics toolkit aimed at empowering artists and technologists, and how can its efficacy in achieving this goal be rigorously evaluated?”

While the previous questions focus on identifying movement systems and translating them into practical artistic applications, this question shifts towards the broader design and evaluation of the toolkit itself. It seeks to determine the best way to structure and present resources in a format that is accessible, engaging, and useful for artists and technologists. Furthermore, it investigates how the toolkit's effectiveness can be measured and validated through user feedback, usability studies, and practical implementation. The findings will ensure that the toolkit not only provides valuable theoretical insights but also serves as a dynamic, interactive resource that meets the needs of its intended audience.

1.3 Report Outline

After the introduction, this thesis investigates the intersection of art, technology, and identity perception, particularly how wearable robotics can influence the way performers and audiences engage with facial expressions and movement in artistic settings. Chapter 2, Literature Review, explores the cultural significance of masks and their historical role in performance arts, alongside advancements in wearable robotics. It also provides an overview of key mechanical systems—such as four-bar linkages, rack-and-pinion mechanisms, and linear actuators—demonstrating how these can be adapted into wearable forms to create dynamic, expressive movement.

Chapter 3, Methodology, details the research design, participant selection, and data analysis techniques, outlining the structured approach taken to develop and evaluate the wearable robotics toolkit. This is followed by Chapter 4, Ideation, which documents the creative and technical brainstorming process that led to the selection of key movement systems for prototyping. The refinement of these ideas into concrete technical and user requirements is covered in Chapter 5, Specification, where the needs of artists, educators, and technologists were analysed to shape the final toolkit design.

The core of this research, Chapter 6, Implementation, focuses on the design and development of multiple prototypes, assessing various mechanisms, materials, and control aspects to determine their feasibility in performance art. The evaluation process and findings are then presented in Chapter 7, Evaluation, where the prototypes and toolkit were tested by participants from diverse backgrounds. This chapter discusses how well the toolkit met its intended goals and highlights areas for improvement.

Finally, Chapter 8, Discussion & Future Work, reflects on the broader implications of these findings, linking them to the artistic and technological landscape. It also provides recommendations for performance artists and suggests potential future research avenues, particularly regarding interactive and customizable wearable robotic systems. Ethical considerations surrounding the use of robotic masks and other wearable devices in performance arts are critically examined in this section. The thesis concludes with Chapter 9, Conclusion, summarizing the key contributions and outlining steps for further development of the toolkit.

2. Background and State of the Art

To ensure a clear understanding of the theory and mechanisms used in this project, this chapter introduces foundational research on identity, faces, and masks, alongside an in-depth exploration of wearable robotics mechanisms. This work builds upon prior research by van der Galiën (2023) on facial identity perception, expanding into the integration of wearable robotics prototypes designed to influence and transform identity perception artistically. Specific prototypes—including a wearable tentacle, a robotic mask, and mechanisms such as rack-and-pinion systems and four-bar linkages—are contextualized within the state-of-the-art advancements in wearable robotics.

2.1 The Connections between Identity, Faces and Masks

In the study of human thought and social behaviour, identity, facial recognition, and masks play a central role. These concepts, rooted in our evolutionary past and cultural traditions, influence how we see ourselves and others (Jack & Schyns, 2015). This section examines the connections between these ideas, looking at the complex nature of identity, our natural ability to identify faces, and the role of masks in performance settings. By exploring these links, we hope to highlight the significant impact these factors have on human communication, art, and cultural stories. The importance of the face in social interaction and our evolutionary history is emphasized by the works of Schmidt and Cohn (2001), who delve into the evolutionary questions surrounding facial expressions and their social implications.

2.1.1 Identity and Masks

To start, van der Galiën delves into the intricate relationship between identity, faces, and masks. She establishes foundational definitions for identity and the self, emphasizing the distinction between personal and social identity. Personal identity is shaped by internal factors and individual experiences, while social identity is influenced by external factors and group affiliations. The self, on the other hand, pertains to one's subjective experience of individuality.

Identity is multifaceted, encompassing both personal and social dimensions. Personal identity is rooted in individual characteristics, while social identity revolves around group affiliations. The self reflects one's subjective experience and individuality.

Faces are pivotal to identity, serving as unique identifiers. From birth, humans are instinctively drawn to faces, indicating their inherent significance in social interactions. The brain processes faces through a specific mechanism, recognizing them as a combination of individual parts. Facial features not only convey personal identity but also hint at social traits, making faces integral to how individuals are perceived in society.

Masks, especially in theatrical contexts, serve as tools to disguise, protect, or transform the wearer. They can be both icons and indexes of identity, concealing the wearer's original identity and projecting a new one. Historical examples include the Greek tragic mask, which conveyed emotions to the audience (Burgholzer, Cheng, Hegenbart, & Hughes, 2021); the Japanese Noh mask, known for its changing expressions based on viewing angles (van der Galiën, 2023); and the Kwakwaka'wakw mask of the Indigenous people of the Pacific Northwest, which showcased multiple layers of identity (Neel, 2019; Dent, 2001).

2.1.2 Theoretical Tools

After exploring identity and masks, van der Galiën delves into the theoretical tools applicable to face-related phenomena, aiming to provide a foundational understanding that can be applied to the project.

The human ability to recognize and differentiate faces is attributed to specific facial features known as facial perception identity markers. Previous research (Abudarham et al., 2019) has shown that there's a set of high-PS features (features with high perceptual sensitivity) crucial for both familiar and unfamiliar face recognition. These features, such as eyes and lips, remain consistent across various conditions, making them reliable indicators of identity. On the other hand, low-PS features, like skin colour or face proportion, can vary under different conditions and are less reliable for identification. The study also posits that the same facial features are used for recognizing both familiar and unfamiliar faces, suggesting that our recognition system is based on a lifetime of experience with familiar faces.

Face pareidolia, the phenomenon where individuals perceive faces in random patterns, is believed to be an inherent human trait. The inclination to recognize faces, even in inanimate objects, is explored in the context of predictive coding theory. Studies by Lhotka, Ischebeck, and Zaretskaya (2023), as well as Barik et al. (2019), suggest that the right FFA (fusiform face area) in the brain plays a crucial role in detecting and recognizing faces, even illusory ones. The eyes and mouth have been identified as essential features for detecting faces in face-like stimuli.

Predictive Processing theory posits that the brain uses past information to anticipate and prepare for potential future events. When encountering unexpected visual stimuli, the brain's activity increases in specific regions, signalling a prediction error. This suggests that the brain relies on prior knowledge and context to interpret new information. Experiences with faces enhance the brain's ability to anticipate and recognize them accurately (Lhotka, Ischebeck, & Zaretskaya, 2023; Barik et al., 2019).

2.1.3 Conclusion

Identity, a multifaceted construct, is deeply intertwined with both individual characteristics and group affiliations, while the self is anchored in personal experiences and individuality. Faces, as unique identifiers, are paramount to this identity, playing an indispensable role in social interactions and being processed distinctively by the brain, underscoring their importance in human communication. This recognition is amplified by the brain's inherent predisposition to discern faces in random patterns and its predictive processing capabilities. Masks, particularly in theatrical settings, further accentuate this relationship between identity and faces. They serve as potent instruments for identity transformation, concealing the wearer's original persona and introducing a new one, emphasising their profound influence on cultural and artistic expressions. Collectively, these insights highlight the profound interplay between identity, facial recognition, and the transformative power of masks in human cognition and societal interactions.

2.2 Methods of Initial Motion and Force Production

Wearable robotics, designed to augment or assist human motion, are fundamentally driven by their actuation mechanisms. This chapter delves into the primary methods of movement, ranging from traditional DC motors to innovative materials that change shape in response to external stimuli. These actuation systems, which encompass the primary sources or mechanisms for initiating force or motion, are pivotal to the functionality of wearable robotic devices. By understanding these key components and their direct role in generating force or motion, we gain valuable insights into the future of wearable robotic applications.

2.2.1 Electric Motors

Electric motors' operation is based on the principles of electromagnetism (Storey, 2017), where a current-carrying conductor experiences a force when placed in a magnetic field. They are divided into the following three categories:

- **DC Motors**: Direct Current (DC) motors operate using a constant voltage source. They are known for their simplicity and are commonly used in applications requiring variable speed and torque. The direction of rotation can be changed by reversing the polarity of the current.
- **Servo Motors**: Servo motors are a type of motor that can operate with precision control of angular or linear position, velocity, and acceleration. They are equipped with a feedback system, typically in the form of an encoder, which allows for precise control of the motion.
- **Stepper Motors**: Stepper motors move in discrete steps, making them ideal for applications requiring precise positioning. They operate by dividing a full rotation into a large number of steps, and the motor's position can be controlled to move and hold at one of these steps

2.2.2 Shape Memory Alloys (SMAs)

Shape Memory Alloys (SMAs) are a unique class of materials that possess the ability to return to a predetermined shape when subjected to a specific thermal stimulus. This property, known as the "shape memory effect," allows these alloys to undergo significant deformation at one temperature and then recover their original, undeformed shape upon heating or cooling as illustrated in figure 2.1 (COMSOL & Christopher, 2018). The underlying mechanism for this behaviour is a phase transformation between martensite (low-temperature phase) and austenite (high-temperature phase). Due to their unique properties, SMAs have found applications in various fields, including medical devices, aerospace, and wearable robotics, where precise actuation and control are required (Frenzel et al., 2015).

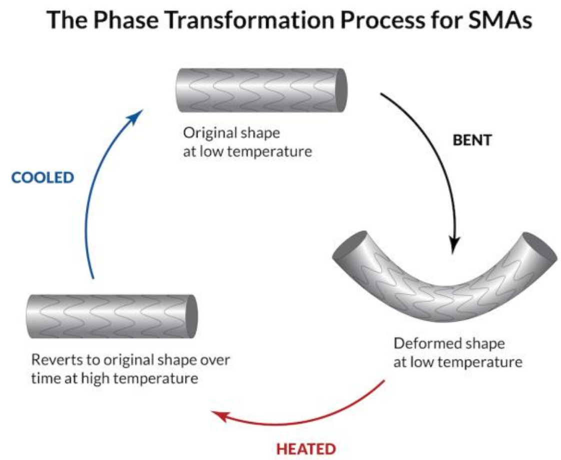

Figure 2.1: Shape memory alloy phase transformation process.

2.2.3 Pneumatic Actuators

Pneumatic actuators utilise compressed air to produce mechanical motion as can be seen in figure 2.2. Their lightweight nature, inherent compliance, and ability to mimic biological muscles make them particularly suitable for wearable robotic applications.

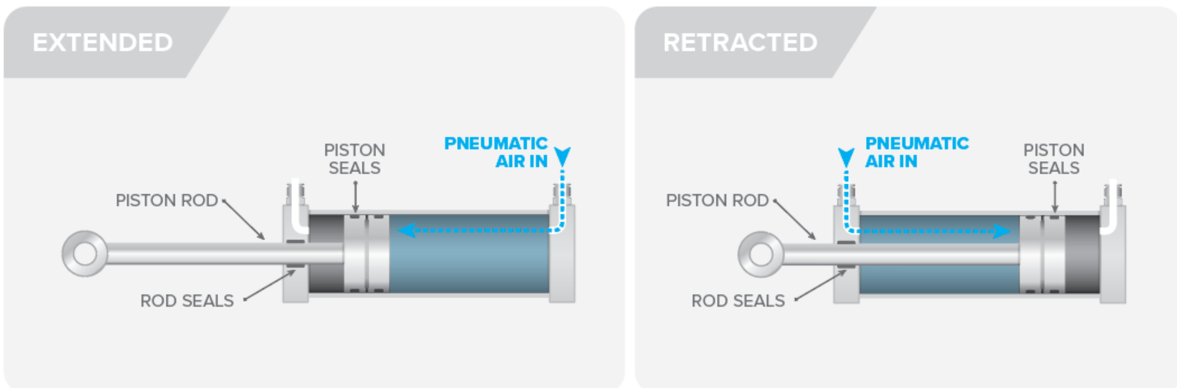

Figure 2.2: Pneumatic actuator components in extended and retracted form.

- **McKibben Muscles:** McKibben muscles, also known as pneumatic artificial muscles (PAMs), are composed of an inner inflatable bladder surrounded by a braided mesh. When inflated, the muscle contracts in length and expands in diameter, mimicking the contractile behaviour of natural muscles as visible in figure 2.3. Their soft and flexible nature allows for safe interaction with the human body, making them ideal for wearable applications (Daerden & Lefeber, 2002).

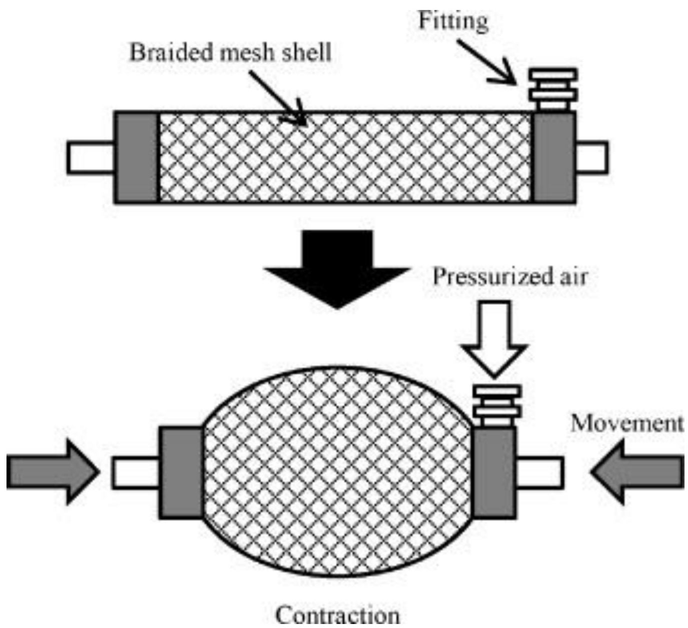

Figure 2.3: Extended and retracted form of McKibben muscles.

- **Bellows:** Bellows are another type of pneumatic actuator that expands, and contracts based on the volume of air inside. Unlike McKibben muscles, bellows have a pleated structure that allows for linear expansion and contraction. They can be designed to produce bending, twisting, or linear motions, depending on the application (Daerden & Lefeber, 2001).

2.2.4 Hydraulic Actuators

Hydraulic actuators are devices that convert the energy from hydraulic fluid pressure into mechanical motion as can be seen in figure 2.4. They operate based on the principle of fluid mechanics, where the pressurised fluid is used to produce linear or rotary motion. These actuators are known for their high force and torque generation capabilities, even in compact form factors. The primary components of a hydraulic actuator system include a hydraulic pump, control valves, and the actuator itself. Due to their power density and precision, hydraulic actuators find applications in various heavy-duty and precision tasks, from construction equipment to robotic arms (Alleyne & Liu, 1999).

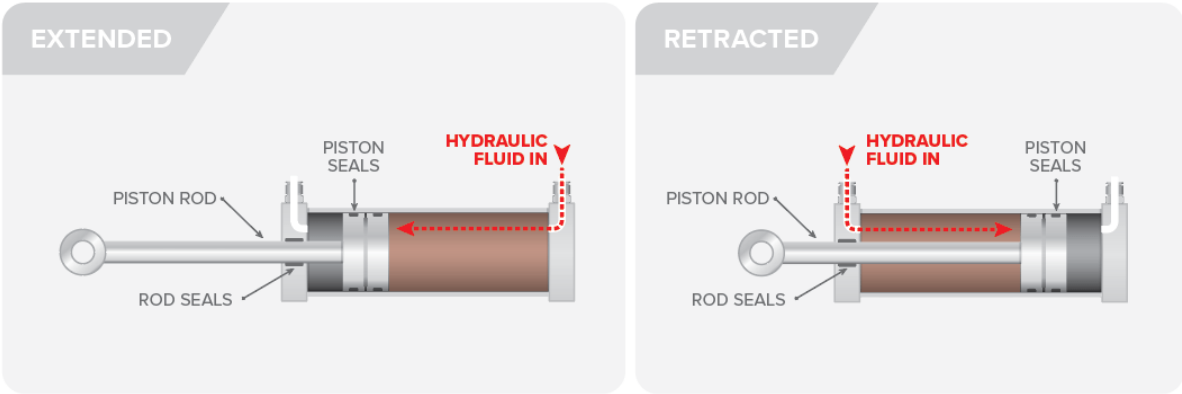

Figure 2.4: Hydraulic actuator components in extended and retracted form.

2.2.5 Electroactive Polymers (EAPs)

Electroactive Polymers (EAPs) are materials that change in size or shape when stimulated by an electric field as seen in figure 2.5. These polymers have garnered significant attention due to their potential to act as artificial muscles, given their ability to produce large strains in response to electrical stimulation (Maser, 2007). EAPs can be broadly categorised into two main groups: ionic and electronic. Ionic EAPs are driven by the movement of ions and typically operate in a wet environment, while electronic EAPs are driven by the movement of electrons. Due to their lightweight, flexibility, and ability to mimic biological muscles, EAPs hold promise for a wide range of applications, especially in the realm of wearable robotics.

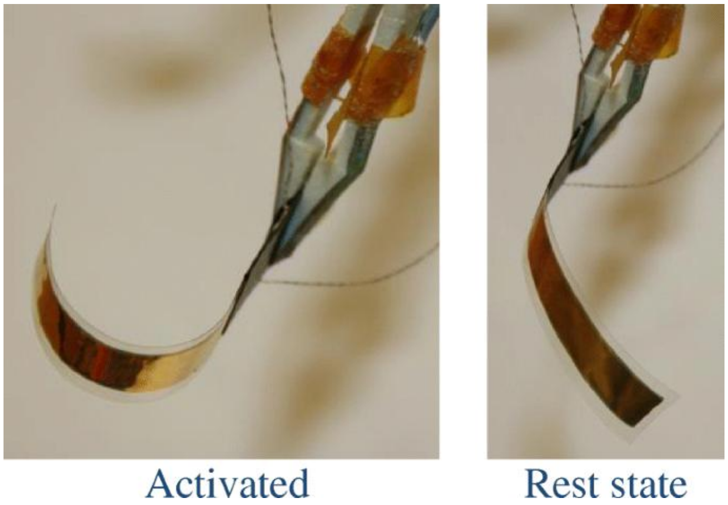

Figure 2.5: Electroactive polymer in activated versus rest state.

2.2.6 Magnetic Actuation

Magnetic actuation refers to the use of magnetic fields to control and manipulate objects or systems. This method capitalises on the interaction between magnetic fields and materials that possess magnetic properties as visualised in figure 2.6. Magnetic actuation offers advantages such as wireless control, which is particularly beneficial in environments where traditional actuation methods might be challenging or hazardous. In the context of wearable robotics, magnetic actuation can be employed to create non-invasive, remotely controlled devices that can be adjusted without direct physical contact. The versatility of magnetic actuation has led to its application in various fields, from micro-robotics to drug delivery systems (Yu et al., 2019).

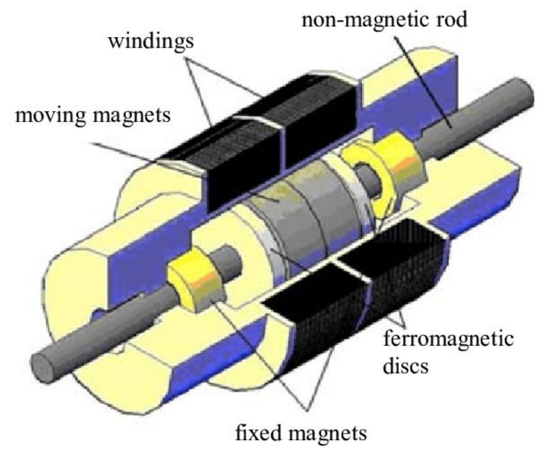

Figure 2.6: Components of a magnetic actuator.

2.2.7 Piezoelectric Actuators

Piezoelectric actuators are devices that utilise the piezoelectric effect to produce mechanical motion, like the device in figure 2.7. The piezoelectric effect refers to the ability of certain materials to generate an electric charge in response to applied mechanical stress and vice versa. When a voltage is applied to a piezoelectric material, it undergoes a dimensional change, leading to mechanical motion. These actuators are known for their precision and rapid response times, making them ideal for applications requiring fine and accurate movements. Due to their compact size, high resolution, and low power consumption, piezoelectric actuators have found applications in various fields, including micro-positioning, medical devices, and wearable robotics (Spanner & Koc, 2016).

Figure 2.7: Example of a piezoelectric actuator.

2.2.8 Thermal Actuators

Thermal actuators convert thermal energy into mechanical energy, leveraging the mismatch in coefficients of thermal expansion (CTE) of different materials to produce motion, as visualised in figure 2.8. When subjected to heat, the materials in the actuator expand at different rates, causing the actuator to move. This principle allows thermal actuators to transform heat from various sources into useful mechanical work. They find applications in micro-electromechanical systems (MEMS), where their compact size and precise actuation capabilities are advantageous. The design and optimization of thermal actuators involve considerations of material properties, thermal sources, and actuation mechanisms to ensure efficient and reliable operation (Sigmund, 2001).

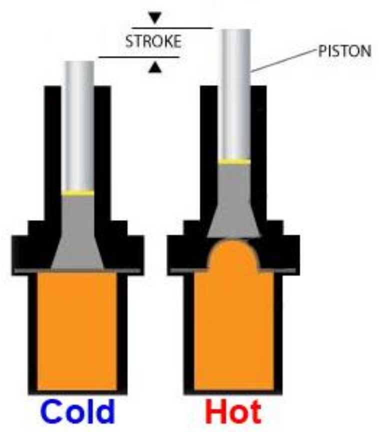

Figure 2.8: A thermal actuator in extended and retracted position.

2.2.9 Elastomeric Actuators

Elastomeric actuators are devices that leverage the inherent properties of elastomers to produce motion or force in response to external stimuli. These actuators are typically made of soft, flexible materials that can undergo significant deformation. One of the most prominent types of elastomeric actuators is the dielectric elastomer actuator. Dielectric elastomers are soft capacitors, where an applied voltage can induce mechanical deformation due to the electrostatic forces between charged electrodes. The significant advantage of elastomeric actuators lies in their ability to produce large strains, lightweight nature, and inherent compliance, making them suitable for applications where soft interactions and adaptability are essential, such as wearable robotics (O'Halloran et al., 2008).

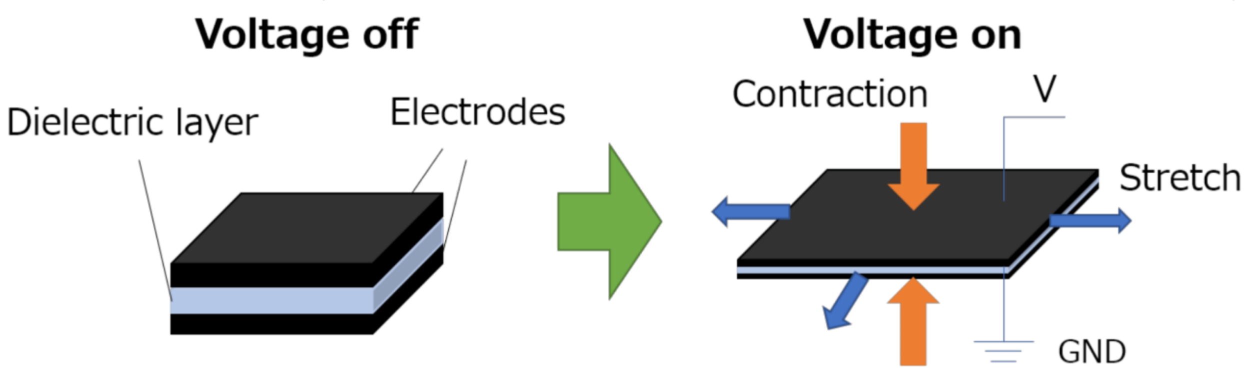

Figure 2.9: Example of an elastomeric actuator in rest state and activated state.

2.2.11 Conclusion

These driving mechanisms, each with its unique characteristics and advantages, collectively contribute to the versatility and adaptability of wearable devices. As wearable robotics grows, understanding these movement methods becomes even more essential. They help us design better devices that work well with our bodies. Some key takeaways are:

1. **Adaptability and Compliance:** Wearable robotics necessitates actuators that are adaptable and compliant to ensure user comfort and safety. Pneumatic actuators like McKibben muscles and bellows, as well as elastomeric actuators like dielectric elastomer actuators, stand out in this regard. Their inherent flexibility and ability to mimic biological muscles make them particularly suitable for wearable applications where soft interaction and adaptability are essential.
2. **Precision and Control:** For applications requiring precise control of movement, electric motors (such as servo and stepper motors) and piezoelectric actuators are more suitable. Servo motors, with their feedback systems, offer precise control of position, velocity, and acceleration, while stepper motors are ideal for applications requiring precise positioning due to their ability to move in discrete steps. Piezoelectric actuators are known for their precision and rapid response times, making them ideal for fine and accurate movements.
3. **Lightweight and Compact Design:** In wearable robotics, the weight and size of the actuation system are critical factors. Electroactive Polymers (EAPs) are advantageous in this aspect due to their lightweight nature. EAPs are promising for their ability to produce large strains while being lightweight and flexible.
4. **Power and Force Generation:** For applications requiring high force and torque generation, even in compact form factors, hydraulic actuators are a viable option. They are known for their high-power density and precision, making them suitable for more heavy-duty tasks in wearable robotics.
5. **Innovative and Emerging Technologies:** Shape Memory Alloys (SMAs) and magnetic actuation represent innovative approaches in wearable robotics. SMAs offer unique actuation capabilities due to their shape memory effect, while magnetic actuation provides the advantage of wireless control, which can be beneficial in certain wearable applications.

In conclusion, the most suitable methods for wearable robotics depend on the specific requirements of the application, including the need for adaptability, precision, compactness, power, and innovative functionalities. A combination of these actuation methods might often be employed to achieve the desired performance in wearable robotic devices.

2.3 Linkage and Movement Systems

In the realm of wearable robotics, while the actuation mechanisms initiate force or motion, it is equally vital to consider how this motion is transmitted, converted, or utilised to achieve the desired outcomes. This subchapter shifts focus from the primary actuation methods to the linkage and movement systems that act as intermediaries. These systems ensure that the generated motion or force is directed appropriately, modified, or adapted to cater to specific applications. By delving into these mechanisms, from traditional transmission systems to innovative movement adaptations, we aim to provide a comprehensive understanding of the components that shape the functionality and versatility of wearable robotic devices, paving the way for future advancements in the field.

2.3.1 Soft Robotics

Soft robotics is an interdisciplinary field that focuses on the design, fabrication, and control of robots using materials that mimic the flexibility and adaptability of biological organisms. Unlike traditional rigid robots, soft robots are made of compliant materials that allow for more versatile movements and interactions with their environment. This flexibility enables soft robots to perform tasks in complex and unstructured environments, making them particularly suitable for applications where safety and adaptability are paramount. The inspiration for soft robotics often comes from nature, with designs mimicking the movements and structures of animals and plants, like the soft robot inspired by and octopus seen in figure 2.10. The inherent compliance of soft robots offers advantages in terms of adaptability, resilience, and safety, especially in human-robot interactions (Majidi, 2018).

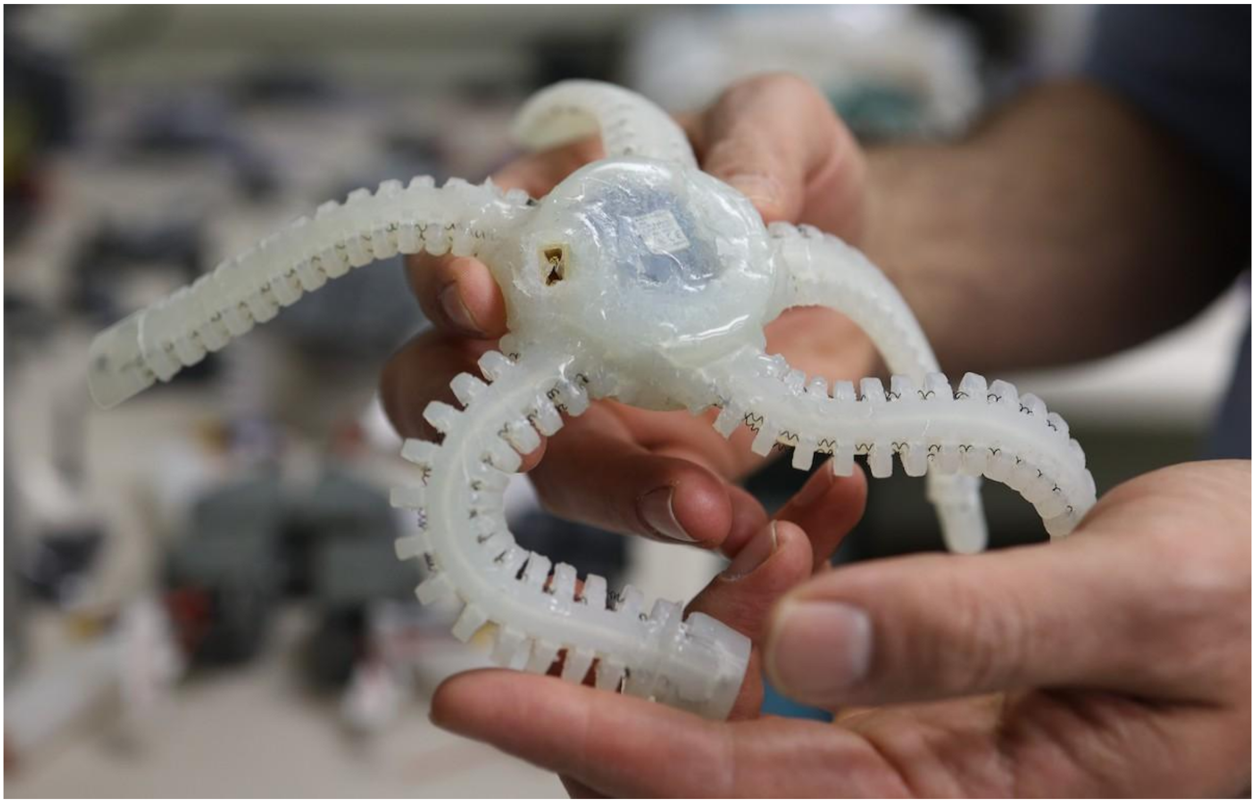

Figure 2.10: A soft robotics "penta-pus", inspired by an octopus.

2.3.2 Cable-driven Systems

Cable-driven systems, often employed in robotics, utilise cables as the primary means of actuation and transmission as visible in figure 2.11. These systems offer a unique combination of flexibility, lightweight construction, and adaptability. The cables, when tensioned, can produce motion by pulling on specific points or structures. This mechanism allows for a wide range of movements and configurations, making cable-driven systems particularly suitable for applications that require adaptability and a high degree of freedom. One of the notable advantages of these systems is their ability to distribute forces across multiple cables, ensuring safety and stability. Moreover, their inherent compliance and soft nature make them ideal for interactions with humans and delicate environments (Lahouar et al., 2009).

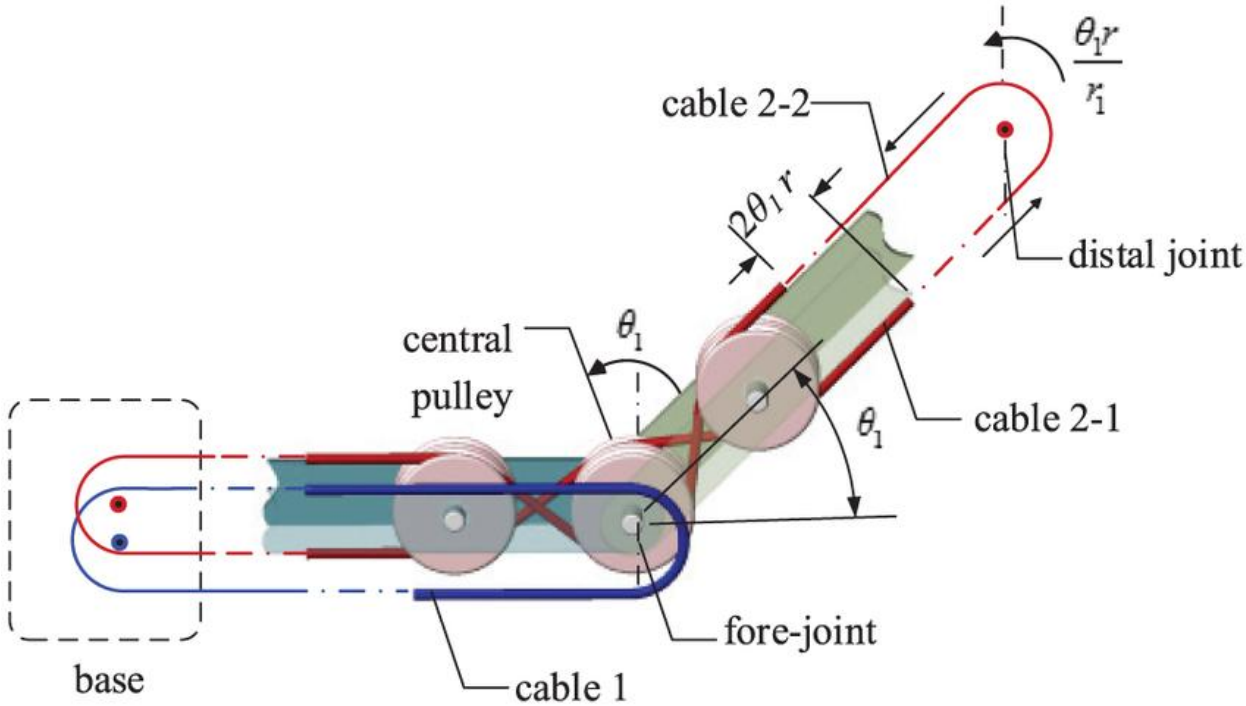

Figure 2.11: Components of a cable drive system mimicking a limb.

2.3.3 Mechanical Springs and Latches

Mechanical springs are devices that store potential energy when they are deformed and release it when they return to their original shape. They can be designed to exert a push, pull, or rotational force. The most common types include coil springs, leaf springs, and torsion springs. Their ability to store and release energy makes them integral components in many mechanical systems, providing shock absorption, force generation, and maintaining contact between surfaces. A basic configuration can be seen in figure 2.12.

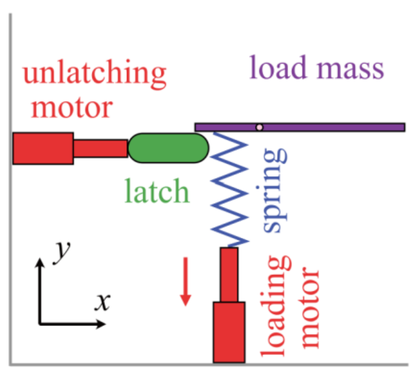

Figure 2.12: Basic configuration of a spring and latch system.

Latches, on the other hand, are mechanical fasteners that join objects together and prevent them from separating. They operate by engaging a mechanism, often spring-loaded, to secure objects in place. Latches are commonly used in doors, gates, and various equipment to ensure they remain closed or in a specific position until intentionally released.

The integration of springs and latches has been explored in various applications, from simple mechanical systems to complex biological organisms, highlighting their versatility and importance in motion and force generation (Longo et al., 2019).

2.3.4 Tendon-driven Systems

Tendon-driven systems have emerged as a promising approach in the domain of wearable robotics, particularly for applications that demand lightweight, adaptable, and intuitive mechanisms. These systems leverage tendons, akin to the biological tendons in our body, to transmit force and motion from actuators to the desired parts of a wearable device, an example can be seen in figure 2.13. The primary advantage of tendon-driven systems lies in their ability to provide a natural and flexible movement, making them especially suitable for wearable applications that require close interaction with the human body.

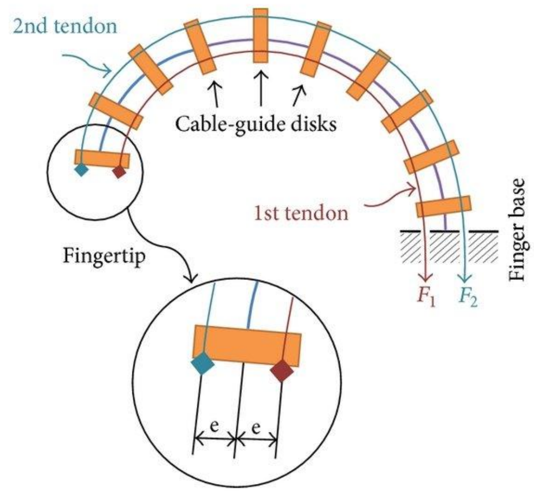

Figure 2.13: A tendon-driven tentacle.

One notable application of tendon-driven systems is in the development of wearable robotic hands. For instance, Kang et al. (2016) presented the "Exo-Glove Poly," a polymer-based tendon-driven wearable robotic hand designed for sanitization in multi-user environments such as hospitals1. Another study by Albaugh, Hudson, and Yao (2019) explored the potential of machine knitting in creating actuated soft objects, emphasising the integration of tendon-based actuation into these objects2. Such advancements underscore the versatility and potential of tendon-driven systems in wearable robotics, offering a blend of adaptability, efficiency, and user-friendliness.

2.3.5 Rack and Pinion Systems

Rack and pinion systems are mechanical arrangements that convert rotational motion into linear motion. This mechanism consists of a circular gear (the pinion) that engages with a linear gear (the rack) as seen in figure 2.14. When the pinion rotates, it drives the rack linearly, either forwards or backwards, depending on the direction of rotation. This conversion of motion is particularly useful in applications where precise linear movement is required.

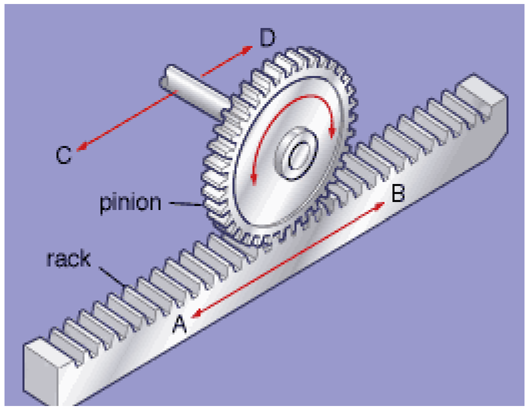

Figure 2.14: Simple rack and pinion illustration.

In the context of wearable robotics, rack and pinion systems can be employed in devices that necessitate controlled linear motion. For instance, a wearable robotic exoskeleton designed to assist with leg movement might utilise a rack and pinion system to ensure precise knee joint extension and flexion. The advantage of such a system lies in its ability to provide consistent and controlled linear motion, which can be crucial for maintaining the safety and comfort of the wearer.

A study titled "Design and Evaluation of a Bowden-Cable-Based Remote Actuation System for Wearable Robotics" by Hofmann et al. (2018) introduced a novel Bowden-cable-based bidirectional remote actuation system for wearable robots. This system incorporated a rack-and-pinion mechanism to reduce the force transmitted through the Bowden cables, allowing for the use of extremely compliant sheaths. The study highlighted the potential of integrating rack and pinion systems in wearable robotics to achieve high power-to-mass and power-to-volume ratios, ensuring accurate force control across various bending angles and the user's full range of motion.

2.3.6 Four-bar Linkages

Four-bar linkages, a fundamental mechanism in the realm of mechanical design, have found their way into the domain of wearable robotics. These linkages, characterised by their four interconnected bars or links, are known for their ability to convert one type of motion into another, often used to achieve specific motion profiles or constraints. In the context of wearable robotics, the adaptability and simplicity of four-bar linkages make them a preferred choice for various applications. As can be seen in figure 2.15, there are four possible configurations to be made with four-bar linkages.

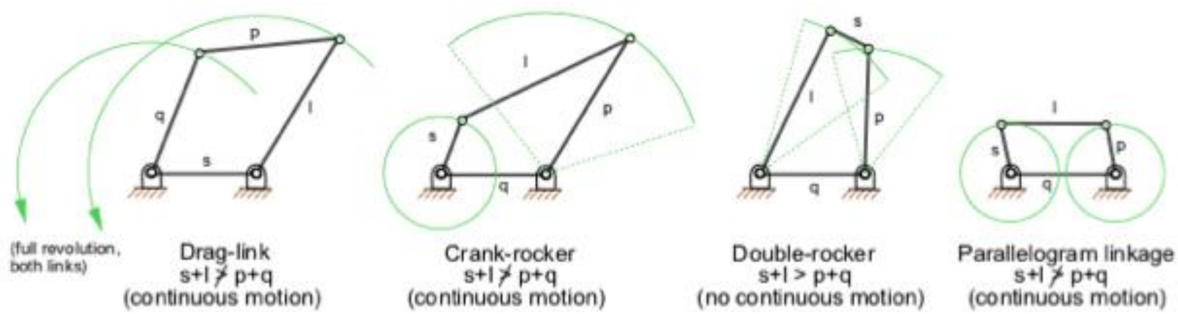

Figure 2.15: The four possible configurations of four-bar linkages.

For instance, a study titled "Quantitative evaluation of hand functions using a wearable hand exoskeleton system" by Kim et al. (2017) highlights the use of four-bar linkages in the design of a hand exoskeleton. This exoskeleton was developed to evaluate hand functions, including finger independence and multi-digit synergy. The system comprised four 4-bar linkages for each finger, allowing for independent flexion and extension of the metacarpal (MCP) and proximal interphalangeal (PIP) joints while measuring the pulling force at each phalanx.

2.3.7 Cam and Follower Mechanisms

Cam and follower mechanisms are fundamental components in many mechanical systems, converting rotational motion into linear or oscillatory motion. The cam, a specially designed rotating element, interacts with a follower, which is typically a rod or lever that moves in response to the cam's profile. As the cam rotates, the follower traces its surface, resulting in a specific motion pattern which is visualised in figure 2.16. This mechanism is particularly useful for producing precise and repeatable movements. In the context of wearable robotics, cam and follower systems can be employed to generate specific motion patterns, such as simulating human pulse waveforms. A notable study by Yang et al. (2019) proposed a compact pulsatile simulator based on a cam-follower mechanism controlled by a DC motor to generate pulse waveforms that mimic human blood pulsations, demonstrating the potential applications of this mechanism in wearable devices.

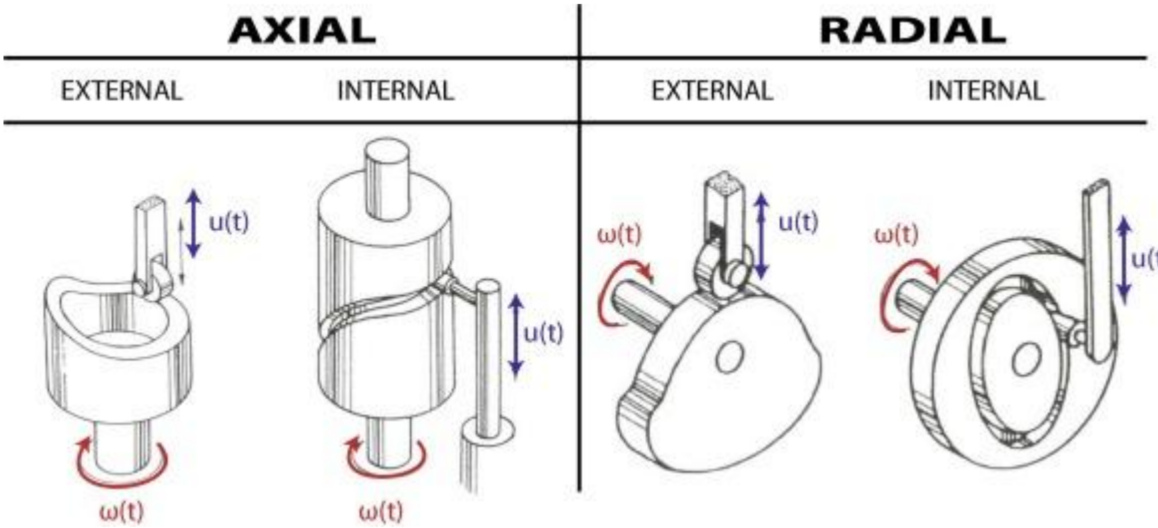

Figure 2.16: Comparison of an axial and radial cam and follower with their external and internal version illustrated.

2.3.8 Scotch Yoke Mechanism

The Scotch Yoke is a mechanism designed to convert rotational motion into linear reciprocating motion as seen in figure 2.17. It primarily consists of two parts: a rolling scotch and a sliding yoke. The yoke is driven by a pin that is eccentrically placed on the scotch. This mechanism is known for its efficiency, particularly in applications requiring low torque.

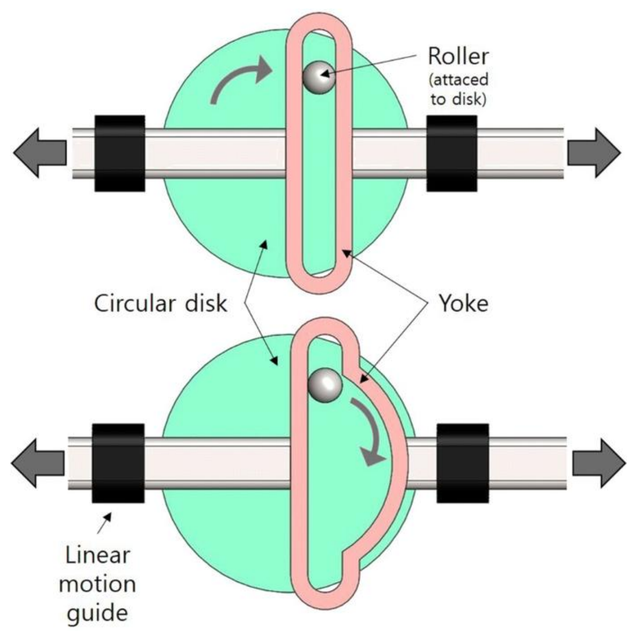

Figure 2.17: Two examples of a scotch yoke mechanism.

In the context of wearable robotics, the Scotch Yoke can be an effective mechanism for achieving precise linear movements. For instance, in microfluidics, where precise flow rates are essential, the Scotch Yoke has been explored as a potential alternative to the conventionally used crank and slider mechanism. Due to its proximity to the source, the Scotch Yoke tends to have reduced energy losses, making it a viable option for applications demanding efficiency and precision. A study by Pramoth Kumar, Akash, and Venkatesan (2016) examined the feasibility of the Scotch Yoke in syringe pumps, which require precise flow rates. Their findings suggest that the Scotch Yoke can achieve maximum velocity efficiently, making it a promising mechanism for various applications, including wearable robotics.

2.3.9 Planetary Gear Systems

Planetary gear systems, also known as epicyclic gear systems, are a set of gears consisting of one or more outer gears, or planet gears, revolving around a central, or sun gear, as visualised in figure 2.18. Typically, they are used in various applications due to their compactness, high power density, and ability to provide high torque from a relatively small form factor.

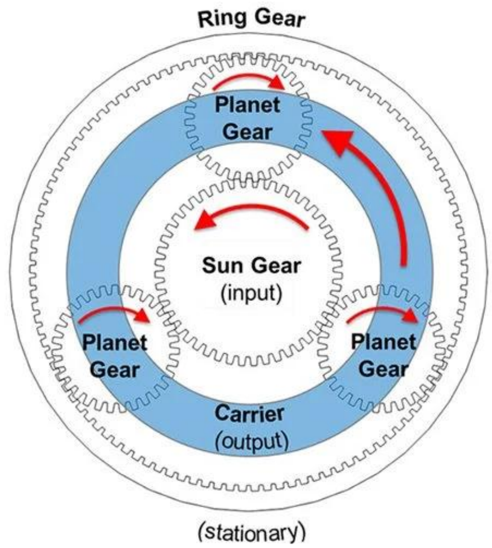

Figure 2.18: Example of a planetary gear system.

In the context of wearable robotics, planetary gear systems offer significant advantages. Terfurth and Parspour (2019) introduced a joint actuator concept for wearable and industrial robotics that leverages the capabilities of planetary gearboxes. Their concept is based on a planetary gearbox coupled with a high-torque electric main drive and additional integrated smaller electric drives. This configuration not only enhances torque output in terms of amplitude, ripple, and dynamics but also facilitates the generation of additional data and the implementation of operating strategies tailored to specific applications. Such advancements underscore the potential of planetary gear systems in wearable robotics, especially when compactness, high torque, and adaptability are paramount.

2.3.10 Artificial Muscles

Artificial muscles, also known as dielectric elastomer actuators (DEAs), are emerging as a promising technology in the field of wearable robotics. Unlike traditional rigid actuators, DEAs offer high energy density, rapid response, and significant actuation strains, often surpassing or mirroring the capabilities of natural muscles. These unique properties position DEAs as potential replacements for current actuator technologies, especially in applications requiring flexibility, adaptability, and lightweight solutions. For instance, DEAs can be employed in powered prosthetic and orthotic devices, where they can overcome the limitations posed by rigid actuators, such as reduced degrees of freedom and increased weight. However, challenges such as high operating voltages, durability concerns, and inherent nonlinearities still need to be addressed for DEAs to be widely adopted in wearable robotic applications. Recent advances in materials, control strategies, and fabrication methods are paving the way to mitigate these challenges, suggesting that DEAs could indeed be the next-generation actuators for bionic and wearable devices as visualised in figure 2.19.

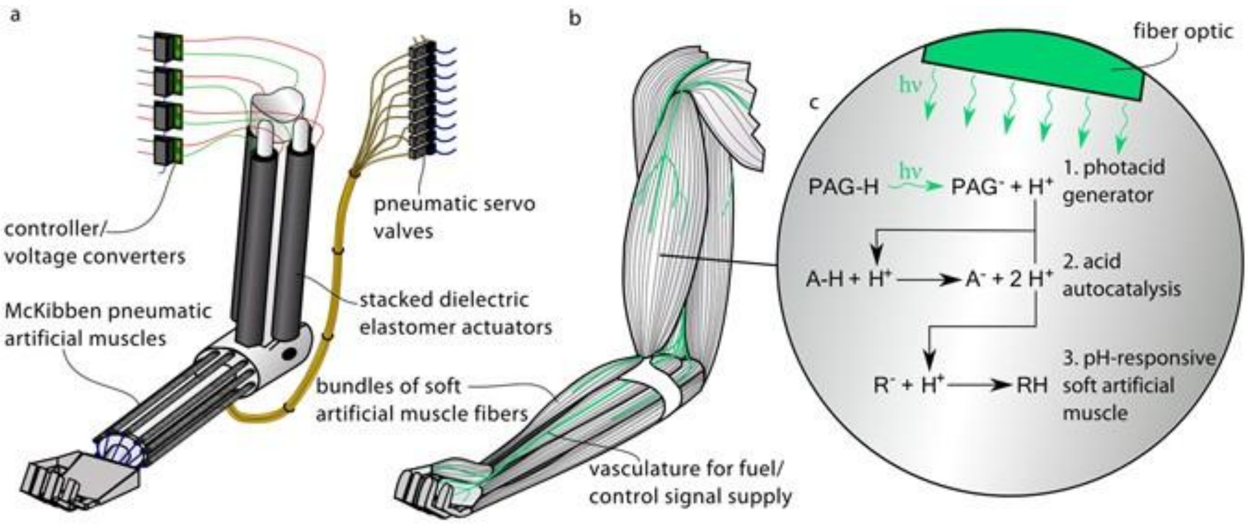

Figure 2.19: Visualisation of (a) current artificial muscles and (b) theoretical future artificial muscles.

2.3.11 Bistable auxetic surface structures

In the domain of wearable robotics, bistable auxetic surface structures have emerged as promising material systems, offering unique deployment capabilities. These structures are based on optimised bistable auxetic cells and can be flat fabricated from elastic sheet materials. Once fabricated, they can be deployed towards a desired double-curved target shape by activating the bistable mechanism inherent in its component cells as seen in figure 2.20. A distinctive feature of these structures is that, once deployed, they remain in a stable state, eliminating the need for complex external supports or boundary constraints. The design process for these structures involves a computational solution that precomputes a library of bistable auxetic cells, covering a range of in-plane expansion and contraction ratios. This ensures the bistability and stiffness of the cell, leading to robust deployment. The planar fabrication state is then computed as a composition of cells that best matches the desired deployment deformation. As each cell expands or contracts during deployment, metric frustration forces the surface towards its target equilibrium state, validating the efficacy of this method (Chen, Panetta, Schnaubelt, & Pauly, 2021).

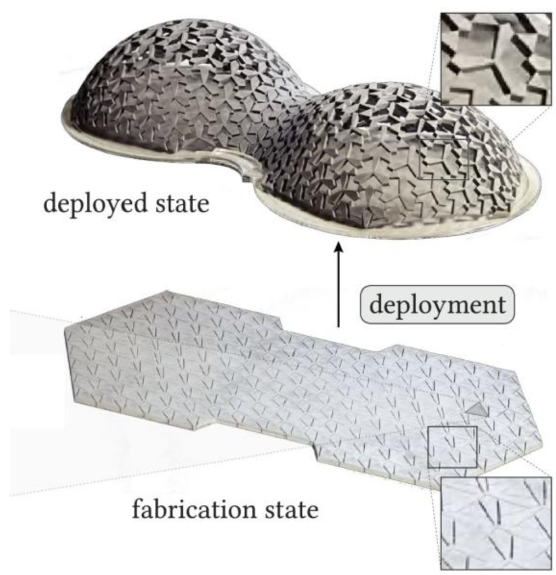

Figure 2.20: A bistable auxetic surface structure in original and deployed state.

2.3.12 Tensegrity Robotics

Tensegrity robotics is an innovative field that explores the use of tensegrity structures in robotic systems. These structures are characterised by a network of isolated components under compression inside a network of continuous tension, resulting in a stable yet flexible form. Tensegrity robots, such as the Reservoir Compliant Tensegrity Robot, leverage these unique structural characteristics to achieve remarkable adaptability and resilience, making them suitable for challenging environments where traditional rigid-bodied robots might fail. The design and control of these robots have been validated through both simulation and hardware prototypes, demonstrating their potential in various applications ("Design and control of compliant tensegrity robots through simulation and hardware validation," Royal Society Publishing).

A notable example of tensegrity robotics in action is the SUPERball, an untethered tensegrity robot developed by NASA's Intelligent Robotics Group. This robot showcases the advantages of tensegrity structures in space robotics, offering a lightweight, cost-effective, and versatile solution compared to conventional space robotics platforms. Its design allows for efficient locomotion and adaptability in unpredictable extraterrestrial terrains, highlighting the promising future of tensegrity robotics in space exploration ("System design and locomotion of SUPERball, an untethered tensegrity robot," IEEE Xplore).

2.3.13 Conclusion

Drawing a conclusion from the chapter on "Linkage and Movement Systems" in wearable robotics, it's evident that the choice of mechanisms significantly influences the effectiveness and applicability of wearable devices. Using the same five measures as in the conclusion of subchapter 2.2, here's a synthesized overview:

1. **Adaptability and Compliance:** Soft robotics and cable-driven systems are particularly noteworthy for their adaptability and compliance. These systems, with their inherent flexibility and ability to mimic biological structures, are ideal for wearable applications that require a high degree of adaptability and safe human-robot interaction. Tendon-driven systems also contribute to this category, offering natural and flexible movement that aligns closely with human biomechanics.
2. **Precision and Control:** Rack and pinion systems, as well as cam and follower mechanisms, stand out for their ability to provide precise and controlled motion. These systems are beneficial in applications where exact linear or specific motion patterns are crucial. Four-bar linkages also contribute to precision and control, especially in applications like hand exoskeletons where specific motion profiles are required.
3. **Lightweight and Compact Design:** Cable-driven and tendon-driven systems are advantageous in terms of lightweight and compact design. Their minimalistic yet effective approach to motion transmission makes them suitable for wearable devices where the weight and bulk of the system are critical considerations.
4. **Power and Force Generation:** Planetary gear systems are notable for their high power density and ability to provide high torque in a compact form factor. This makes them

suitable for more robust wearable applications where efficient power transmission is essential.

5. **Innovative and Emerging Technologies:** Artificial muscles, including dielectric elastomer actuators, represent the forefront of innovative technologies in wearable robotics. Their high energy density, rapid response, and significant actuation strains position them as potential game-changers in the field. Bistable auxetic surface structures and tensegrity robotics also fall into this category, offering unique deployment capabilities and structural advantages that could revolutionise how wearable devices are designed and function.

In conclusion, the most suitable linkage and movement systems for wearable robotics are determined by the specific needs of the application, including adaptability, precision, compactness, power generation, and the incorporation of innovative technologies. A combination of these systems, tailored to the unique demands of the wearable device, is often necessary to achieve optimal performance and user experience.

2.4 State of the Art

In the world of wearable robotics, the use of robotic faces and masks stands out as a fascinating area of study. As technology advances, the lines between human and machine become more intertwined, leading to new insights about identity and how we express ourselves. This subchapter looks at how robotic faces and masks are being used today, from medical fields to movies and art. Through these examples, we aim to highlight the growing role of robotics in shaping how we think about and interact with facial expressions and identities.

2.4.1 Yin Yu's "Soft Tectonics" Series

Yin Yu's art pieces "Soft Voss"(figure 2.21) and "OctoAnemone," from her "Soft Tectonics" series at the University of California, Santa Barbara, are great examples of how art can blend with technology. These works use 3-D printing, sound activation, and flexible materials like silicon and vinyl. This shows Yu's interest in how people interact with robots and what that means for us. "Soft Voss" is a standout piece. It's wearable art that reacts to sound. It combines design, soft materials, and digital tech. The piece uses sounds from the environment, picked up by

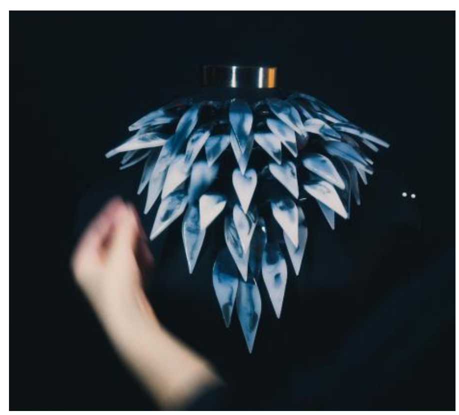

Figure 2.21: Yin Yu’s Soft Voss.

microphones, to move and change. This creates a special experience that mixes the wearer, their surroundings, and the technology in a new way.

"OctoAnemone" is different. It's an imaginative piece that looks like a sea creature and represents a future life form. It makes us think about how today's world could shape the life of tomorrow. It's like a bridge between what we know and what could be, guessing at how future creatures might look. Yin Yu's work in both "Soft Voss" and "OctoAnemone" mixes art, technology, and interactive design in a fresh way. It challenges old ideas about art and makes us think about how people and technology are coming together.

2.4.2 JIZAI ARMS

Figure 2.22: JIZAI ARMS by Nahoko Yamamura.

In the realm of wearable robotics, the concept of "JIZAI ARMS," a supernumerary robotic limb system, marks a significant advancement. This system seen in figure 2.22, introduced by Nahoko Yamamura and colleagues, represents a leap in human augmentation technology. The JIZAI ARMS consist of a wearable base unit with six terminals, onto which detachable robot arms can be attached. These arms are controllable by the wearer, fostering a unique form of social interaction among users. This system allows for the exchange of robotic arms between wearers, paving the way for a new kind of social interaction in a cyborg society. The development of JIZAI ARMS involved an interdisciplinary collaboration, bringing together human augmentation researchers, product designers, system architects, and manufacturers. This collaboration aimed to balance the technical complexity of the system with aesthetic considerations, essential for integrating such technology into daily life. The paper provides an autobiographical account of the authors' experiences using the JIZAI ARMS, offering insights into the potential social interactions and communication dynamics among digital cyborgs. This research not only contributes to the field of human augmentation but also opens up new possibilities for human-machine integration, highlighting the potential for such technologies to transform social interactions and personal experiences.

2.4.3 Calico

The field of wearable robotics has taken a significant leap forward with the development of Calico, a small wearable robot created by researchers at the Small Artifacts Lab (SMART LAB) at the University of Maryland. Weighing a mere 18 grams, Calico represents a new frontier in personal robotics, designed to navigate across clothing via a specialised track as seen in figure 2.23. This innovative approach allows Calico to perform a variety of tasks, from acting as a stethoscope to monitor heart and lung sounds, to guiding users through fitness routines. The robot's ability to carry a 20-gram payload and move at speeds between 115 and 227 millimetres per second showcases its efficiency and versatility. Moreover, its low-power design, featuring a battery that lasts over 8 hours in idle state or 30 minutes with continuous movement, highlights the practicality of integrating robotics into daily wear. One of the most notable challenges overcome in Calico's development was localization - determining the robot's position on the clothing. The solution involved embedding neodymium magnets into the clothing track at regular intervals, which Calico detects using onboard sensors to navigate accurately. This system proved highly effective, with the robot consistently identifying each marker. The potential applications of Calico are vast and varied, ranging from medical uses like sensing vital signs and fall detection to lifestyle applications such as dance instruction and workout guidance. The concept of data physicalization is particularly intriguing; for instance, using the robot to represent progress on tasks by moving up the arm. The possibility of personalising Calico with accessories like fur and googly eyes adds a playful, customizable element to this cutting-edge technology. Calico is not just a functional tool; it's a conversation starter and a glimpse into a future where wearable robots are an integral part of our daily lives, enhancing our capabilities in both practical and entertaining ways.

Figure 2.23: Calico by the Small Artifacts Lab.

2.4.4 Homo Viridis

Figure 2.24: “Homo Viridis”, wearable bellows.

Homo Viridis is a groundbreaking installation that merges human senses, technology, and the natural world in a unique way. It challenges us to think differently about how we interact with other living beings and our environment. The centrepiece of this experience is a wearable soft robotic skin, designed to respond to interactions with a plant. This skin is not just a piece of technology; it's a bridge between human and plant experiences. When the plant is touched, the skin inflates and changes shape, creating a tangible, physical response that the wearer can feel (see figure 2.24). This innovative design allows for a kind of communication that goes beyond words or sight, offering a direct, physical connection to the natural world. The name 'Homo Viridis', meaning 'green human', aptly reflects this new, vibrant way of interacting with our surroundings. The development of the soft robotic skin is a key aspect of Homo Viridis. Unlike traditional robotics, this skin is made to be flexible, soft, and organic in its movements, mirroring the natural world it seeks to connect with. The creation process involved combining elements of robotics with materials that could mimic the fluidity and responsiveness of living organisms. The challenge was to make a technology that could not only react to external stimuli but also convey a sense of life and natural movement. The result is a wearable piece that moves and adapts in a way that feels alive, providing an immersive experience that goes beyond visual or auditory interactions. This soft robotic skin represents a significant step forward in the field of interactive installations, offering a glimpse into a future where technology can create deeper, more intuitive connections between humans and the natural world.

2.4.5 Tim Hawkinson’s “Emoter”

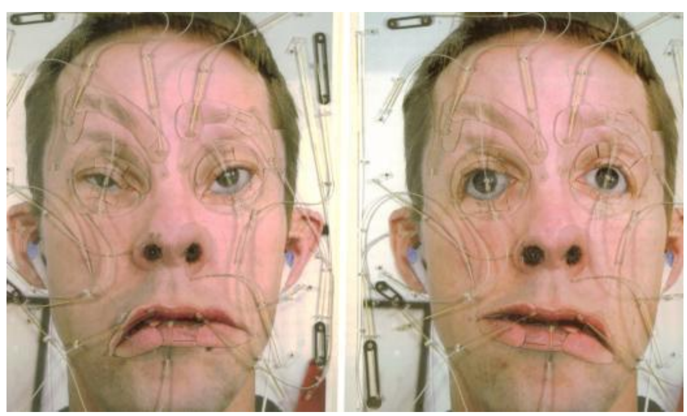

Figure 2.25: Tim Hawkinson’s Emoter.

Tim Hawkinson's "Emoter" (figure 2.25) is an intriguing artwork that exemplifies the intricate blend of art and mechanical engineering. This piece is particularly significant for its innovative use of mechanical systems to alter and reinterpret facial expressions, a concept that is both artistically and technically challenging. The artwork utilises a complex arrangement of pulleys and levers, meticulously designed to manipulate a photograph of the artist's own face. Each component in this system is carefully calibrated to adjust various parts of the face, such as the eyebrows, lips, and eyes, allowing the static image to convey a range of emotions and expressions. This mechanical orchestration not only demonstrates Hawkinson's mastery in mechanics but also his deep understanding of the human face as a canvas for emotional expression.

The "Emoter" goes beyond being a mere artistic creation; it is a profound exploration of the relationship between human identity and mechanical intervention. By transforming his facial expressions through a mechanical medium, Hawkinson challenges the viewer to reconsider the concept of identity in the age of technology. The artwork raises questions about the authenticity of emotions in a world increasingly dominated by artificial intelligence and robotics. It also reflects on the potential of machines not just as tools for practical purposes but as instruments capable of influencing and redefining human expression. The "Emoter," while not a scholarly piece, stands as a testament to the limitless creative possibilities that emerge at the intersection of art, technology, and human emotion, pushing us to ponder the evolving boundaries of self-expression and identity in the modern world.

2.4.6 PneuAct

The advancements at MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) in developing "PneuAct," a rapid design tool for soft pneumatic actuators, mark a significant progression in the field of wearable robotics. These actuators (figure 2.26), powered by compressed air and equipped with sensing capabilities, are advantageous in applications like assistive wearables, robotics, and rehabilitative technologies.

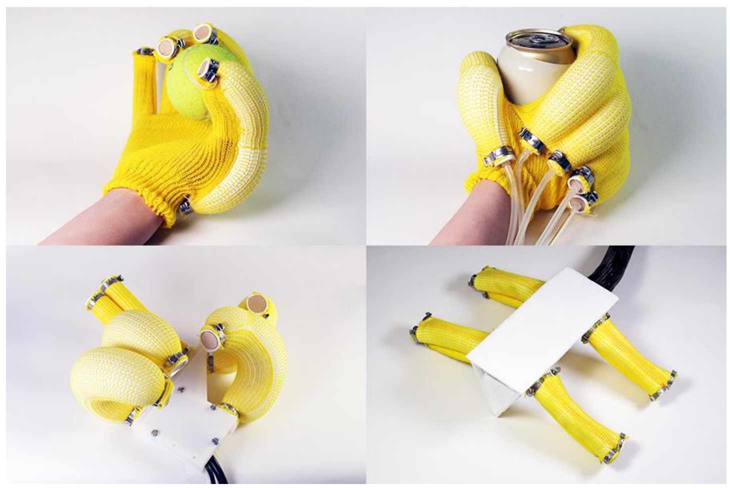

Figure 2.26: PneuAct, a soft pneumatic actuation system.

The PneuAct system utilises a machine knitting process to fabricate actuators integrated with conductive yarn, allowing them to sense touch. This approach has enabled the creation of various prototypes, including an assistive glove and a pneumatic walking quadruped (see figure 2.26).

This innovative design tool addresses previous bottlenecks in the creation of dynamic devices, which typically required manual design and extensive trial-and-error testing. PneuAct's method combines elastic and sensing stitches, facilitating programmed bending and real-world feedback incorporation. Notable applications include a robot that responds to human touch and an assistive glove designed to aid finger movement, useful for individuals with injuries or limited mobility.

While the design of PneuAct is groundbreaking, a notable limitation is their accessibility to the public. The sophisticated nature of these systems, which involves a complex computer simulation together with a custom-built advanced knitting machine, renders them largely inaccessible to everyday users. This gap highlights the need for further development in making these innovative technologies more user-friendly and widely available, ensuring that the benefits of wearable robotics can be extended beyond specialised applications to more commonplace, everyday use.

2.4.7 Kobakant

Kobakant's approach to wearable technology integrates art and design with electronic textiles, offering a unique perspective on wearable tech (Greinke et al., 2019). This initiative, brought to life by artists Hannah Perner-Wilson and Mika Satomi, ventures beyond traditional uses of technology, embedding an artistic flair into wearable devices. Through their platform www.kobakant.at/DIY/, they unfold a rich tapestry of projects, tutorials, and insights dedicated to integrating technology with textile crafts.

The core ethos of Kobakant emphasizes the transformation of technology into a personal, tactile, and understandable medium. Their innovative projects transcend conventional boundaries, marrying the functional with the expressive. Examples include garments that double as musical instruments or jewellery that senses and visualizes bodily functions. This approach not only demystifies electronics but also redefines them as elements of personal expression and identity.

Kobakant's influence extends into wearable robotics by underscoring the significance of creativity, personalization, and storytelling in technology. Their commitment to open-source principles and community involvement mirrors the ethos of collective learning and interdisciplinary collaboration. The fusion of soft circuitry and smart textiles they advocate for provides valuable insights into flexible, user-centred design, inspiring a more inclusive and creative approach to developing wearable robotic applications.

2.4.8 Hackaday

Hackaday.com emerges as a vital platform within the tech community, especially for enthusiasts delving into the realms of robotics and wearable technology (Horvath et al., 2015). The website acts as a melting pot for innovators, offering a space to share, discover, and discuss various projects encompassing a spectrum from hardware modifications to the frontiers of wearable tech.

The significance of Hackaday in the landscape of wearable robotics lies in its foundational spirit of hacking — the art of modifying, repurposing, and innovating to extend the capabilities of existing technology. The community-driven projects showcased on the site cover an impressive range of wearable innovations, from DIY health monitors to advanced motion-sensing attire. These contributions highlight the platform's role in advancing technical knowledge, creativity, and problem-solving skills within the wearable tech community.

Hackaday's ethos of openness and collaboration significantly enriches the field of wearable robotics. By facilitating the exchange of detailed project documentation, code, and practical insights, the platform ensures that technological advancements are accessible to a broad audience. The culture of sharing and competition fostered by Hackaday not only propels innovation but also democratizes the development process, making sophisticated wearable technologies attainable and understandable for hobbyists and experts alike.

2.4.9 Conclusion

This chapter has explored how wearable robotics serves as a medium for redefining identity, expression, and interaction in performance art. Projects such as Soft Tectonics, JIZAI ARMS, and Tim Hawkinson's Emoter illustrate the potential of movement-based augmentation in challenging traditional notions of facial and bodily identity. These works emphasize key design principles—

flexibility, adaptability, and interactive feedback—which inform how wearable robotics can merge seamlessly with human expression.

In considering how robotics can transform facial identity perception, various movement systems have been analysed for their artistic applications. Soft robotics enables fluid, organic transformations, while mechanical linkages such as rack-and-pinion systems and four-bar mechanisms introduce structured yet expressive motion. The ability to dynamically alter a performer's presence through these systems offers new possibilities in storytelling, stage presence, and audience engagement.

Beyond technical aspects, this review has highlighted the importance of open-source collaboration and accessibility in wearable robotics. Platforms like Kobakant and Hackaday showcase how knowledge-sharing fosters creative experimentation, ensuring that technological advancements remain available to a broad audience. By integrating these insights, the wearable robotics toolkit aims to bridge the gap between technical feasibility and artistic innovation, equipping artists with adaptable movement systems to expand the boundaries of identity and performance.

2.5 Categorisation of Mechanisms

The exploration of wearable robotics is an intricate dance between engineering and ergonomics, where the actuator or movement system is the cornerstone of user experience. This chapter delves into the multifaceted criteria that gauge the effectiveness and appropriateness of these systems. We consider a spectrum of factors, from the tangible—like the integration with the human form and the comfort it affords—to the technical, such as energy consumption and the sophistication of control. These elements are critical in steering the trajectory of wearable robotics, ensuring they are not only advanced but also user-centric and socially beneficial (Martinez-Hernandez et al., 2021).

2.5.1 Safety Considerations

In the field of wearable robotics, ensuring safety is as crucial as the technology itself. This aspect stands alone, not to be mixed with other factors like comfort or efficiency. The best kind of actuator is one that includes well-thought-out safety features. These are the safeguards that keep both the person using the device and everyone around them secure. Such features prevent accidents and make sure that the wearable robot is a helpful tool, not a source of danger. On the other hand, if an actuator doesn't have these necessary safety checks, it's not up to par. It could be risky, which is a serious downside. Safety features are not just add-ons; they are essential parts of making wearable robots that can be trusted and used widely (Okpala et al., 2022).

2.5.2 Integration and Comfort

Integration and comfort are paramount in the design of wearable robotics. The ideal actuator should not only fit snugly against the body but also move in sync with it, as if it were a part of the wearer's own anatomy. This seamless integration is achieved through meticulous attention to biomechanical compatibility, ensuring that the device complements the natural movements of the human body. Actuators that excel in this category are typically designed with a user-centric approach, prioritising a lightweight structure and a form-fitting silhouette to enhance the overall experience (Bostelman, Messina, & Foufou, 2017). Conversely, actuators that are bulky or rigid can disrupt the wearer's natural biomechanics, leading to discomfort and a hindered range of motion, which are clear indicators of suboptimal design.

Optimal: Actuators that are lightweight and conform to the body's contours, enhancing the wearer's movement without causing strain or discomfort.

Suboptimal: Clunky systems that clash with the body's mechanics, leading to discomfort and impeded mobility.

2.5.3 Price and Accessibility

The cost and accessibility of actuators are critical factors that determine their adoption and scalability. Affordable, accessible actuators promote broader usage, crucial for expanding wearable robotics, especially in artistic endeavours (Meyer, Gassert, & Lambercy, 2021). This category now also considers the availability of the technology, with the best actuators being those that offer high functionality at a low cost and are readily available to consumers. High prices and limited accessibility are significant obstacles that can prevent the widespread use of these technologies, making them less optimal to be recommended to artists.

Optimal: Cost-effective and widely available actuators.

Suboptimal: Prohibitively expensive systems that hinder widespread adoption due to their cost and limited availability.

2.5.4 Durability

Durability assesses an actuator's resilience and longevity, with optimal actuators resisting wear and environmental conditions, essential for user trust and sustainable application (Bogue, 2017). Actuators that are built to endure, resisting wear and environmental stresses, are the most optimal. They promise longevity and reliability, which are essential for user trust and the sustainable adoption of wearable robotics. On the other hand, actuators that are prone to damage or require frequent maintenance are less ideal, as they can lead to increased costs and inconvenience over time.

Optimal: Durable actuators built to last, capable of withstanding rigorous use and environmental challenges.

Suboptimal: Delicate systems that require frequent maintenance or are easily compromised by external conditions.

2.5.5 Control Complexity and Error Handling

The complexity of controlling wearable robotics and their ability to handle errors effectively are pivotal for ensuring a positive user experience. Intuitive actuators with robust error management systems enhance user confidence and accessibility (Kapeller & Fosch-Villaronga, 2020). Actuators that require extensive technical knowledge to operate or have inadequate error management are less desirable, as they can be intimidating and off-putting to users.

Optimal: Intuitive control systems with robust error-handling capabilities, ensuring safety and ease of use.

Suboptimal: Overly complex control systems that are error-prone and challenging for the average user to manage.

2.5.6 Energy Efficiency and Wearability of Power Source

Energy efficiency and the practicality of the power source are intertwined aspects that affect the usability of wearable robotics. Optimal actuators use energy judiciously and come with non-intrusive power sources, allowing extended use and mobility (Babič et al., 2021). In contrast, systems that consume a large amount of power or have cumbersome power sources detract from the wearability and convenience of the device.

Optimal: Energy-savvy actuators with unobtrusive, wearable power sources that support extended use.

Suboptimal: Energy-intensive systems with bulky power solutions that limit mobility and usage duration.

2.5.7 Ease of Embedding and Construction

The ease with which an actuator can be embedded into garments or other platforms, as well as the simplicity of its assembly, are crucial for user adoption. Actuators that score high in this category are those that can be easily incorporated into a variety of applications without the need for specialised skills or tools, making them more accessible to a wider range of users. The optimal systems are those that encourage DIY efforts and innovation, while those that are complex and inaccessible to the average user score poorly (Thalman & Artemiadis, 2020).

Optimal: User-friendly actuators that offer straightforward embedding into various platforms and easy assembly, even for non-specialists.

Suboptimal: Actuators that are cumbersome to integrate and require specialised knowledge and tools to construct.

2.5.8 Conclusion

The categorization of mechanisms based on their importance is a crucial aspect for advancing this study, particularly in the context of artistic applications. This subchapter has meticulously outlined these categories, emphasising their significance in the development and implementation of wearable robotic systems.

1. **Safety Considerations**: At the forefront is the paramount importance of safety. Ensuring that wearable robotics are equipped with comprehensive safety features is non-negotiable. These features are essential for protecting both the user and those around them, making safety the top priority in wearable robotics design.
2. **Integration and Comfort**: Following closely is the emphasis on integration and comfort. The success of a wearable robotic system hinges on its ability to seamlessly blend with the human body, enhancing rather than hindering movement. This requires a deep understanding of biomechanics and a user-centric design approach.
3. **Price and Accessibility**: The third critical factor is the cost and accessibility of actuators. Making these technologies affordable and readily available is key to their widespread adoption, especially in artistic fields where budget constraints are often a significant consideration.
4. **Durability**: Durability is another vital aspect, ensuring that the actuators can withstand regular use and environmental factors. Longevity and reliability are crucial for building user trust and promoting sustainable use of wearable robotics.
5. **Control Complexity and Error Handling**: The ease of control and robust error-handling capabilities are essential for a positive user experience. Systems that are intuitive and user-friendly will be more readily embraced by a broader audience.
6. **Energy Efficiency and Wearability of Power Source**: The energy efficiency of actuators and the practicality of their power sources are also important. Devices that can operate for extended periods without cumbersome power solutions are more desirable for continuous use.
7. **Ease of Embedding and Construction**: Lastly, the ease with which actuators can be integrated into various platforms and their simplicity in assembly are crucial for encouraging innovation and DIY efforts, making them more accessible to diverse users.

This ranking highlights the multifaceted nature of wearable robotics and underscores the importance of a holistic approach in their development. By prioritising these categories, designers and engineers can create wearable robotic systems that are not only technologically advanced but also user-friendly, safe, and accessible, thereby enhancing their applicability in artistic and other creative domains.

2.6 Conclusion

This chapter has explored the intersection of wearable robotics and artistic expression, investigating how movement systems can be utilized to innovate in facial identity perception. Through case studies on JIZAI ARMS, Soft Tectonics, Tim Hawkinson's Emoter, and other wearable robotics projects, we have identified key principles that inform the development of robotic movement systems for artistic applications. These insights provide direct answers to the guiding research questions while shaping the ideation phase of this project.

"What movement systems in robotics can be harnessed to innovatively design wearable devices that artistically transform facial identity perception?"

The examination of existing projects suggests that different robotic movement systems allow for varying degrees of expressiveness. Soft robotics and pneumatic actuators provide smooth, organic motion, making them suitable for lifelike transformations of facial features or extensions of the body, such as the wearable tentacle prototype. Meanwhile, mechanical systems like rack-and-pinion linkages and four-bar mechanisms allow for controlled, predictable movements, which can be applied in masks or exoskeletal augmentations to create animated, exaggerated expressions.

"What are the primary and emerging movement systems utilised in the field of robotics, and how do they differ in terms of functionality, adaptability, and efficiency?"

The literature highlights a range of movement systems applicable to wearable robotics, each with distinct benefits and constraints. Shape memory alloys (SMAs) offer compact actuation but have slow response times, making them less suitable for rapid artistic expression. Pneumatic actuators, seen in projects like Soft Tectonics, allow for lightweight and adaptable movement but require external air sources. Cable-driven systems, like those used in JIZAI ARMS, enable precise and scalable actuation, making them a strong candidate for integration into wearable masks and facial articulation systems.

"Which movement systems are best suited for wearable applications in terms of comfort, safety, and integration with the human body?"

For wearable applications, considerations such as weight, heat dissipation, and mobility restrictions play crucial roles in determining usability. Pneumatic and elastomeric actuators stand out as safe, lightweight, and adaptable solutions, allowing for direct contact with the human body. Exoskeletal linkages, while structurally rigid, offer precise motion control but may limit flexibility, requiring thoughtful design to avoid user discomfort.

"How can wearable movement systems be innovatively applied to create artistic expressions that influence facial identity perception?"

Drawing from projects like the Emoter and JIZAI ARMS, this research indicates that movement can redefine identity perception by exaggerating facial expressions or introducing non-human gestures. Masks with embedded actuators can dynamically shift features, distorting or amplifying emotions in real-time. Meanwhile, wearable appendages, such as the tentacle prototype, extend bodily movement into new expressive dimensions, reinforcing the idea that identity is not static but rather fluid and adaptable through robotics.

"What is the optimal structure, content composition, and sharing method for a wearable robotics toolkit aimed at empowering artists and technologists, and how can its efficacy in achieving this goal be rigorously evaluated?"

The open-source principles demonstrated by KOBAKANT and Hackaday highlight the importance of accessibility in wearable robotics. This thesis will incorporate these insights into the design of a modular, structured, and community-driven toolkit. The toolkit will be evaluated based on its ability to provide users with clear pathways from conceptualization to implementation, ensuring that artists can experiment freely while receiving structured technical guidance.

In summary, the findings of this chapter provide a foundation for the ideation phase by directly linking movement systems to artistic and performative applications. The prototypes developed will leverage the strengths of both organic (soft robotics, pneumatic actuators) and structured (rack-and-pinion, cable-driven) movement to offer a range of expressive possibilities. Furthermore, the collaborative potential of open-source platforms informs the structure of the toolkit, ensuring that accessibility and adaptability remain at the core of this project’s development.

3. Methods and Techniques

This chapter outlines the methods and techniques employed to develop the wearable robotics prototypes and the toolkit websites. The approach taken follows the Creative Technology Design Process (Mader & Eggink, 2014), which structures projects into four iterative phases: Ideation, Specification, Realization, and Evaluation as seen in figure 3.12. This framework supports continuous refinement, ensuring that the final product aligns with both the research objectives and user needs.

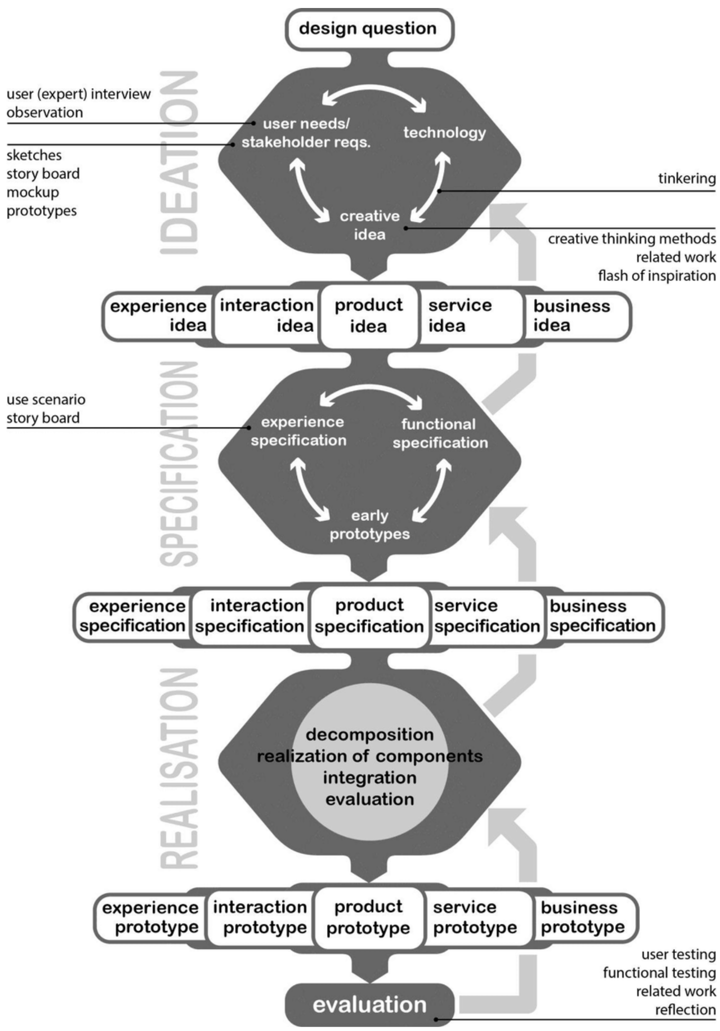

Figure 3.1 The Creative Technology Design Process by Mader and Eggink (2014).

The Ideation phase focused on conceptual exploration, drawing from literature, case studies, and stakeholder input to identify potential movement systems that could be integrated into wearable robotics. This stage generated multiple early concepts, including robotic masks, soft robotic tentacles, and actuation mechanisms such as four-bar linkages and syringe-driven actuators. The ideation process also considered different methods of presenting and disseminating this knowledge, laying the groundwork for the toolkit website.

The Specification phase translated these initial ideas into concrete requirements. Through stakeholder discussions and iterative testing, functional and non-functional requirements were established for both the prototypes and the online toolkit. This phase ensured that the selected movement systems were feasible for artistic applications and that the website's structure provided clear and accessible learning pathways for artists and technologists.

The Realization phase involved prototyping and implementation. Physical prototypes of the wearable robotics systems were developed, integrating selected actuation methods and materials. Simultaneously, the toolkit website was built using HTML, CSS, and Bootstrap, hosted on GitHub Pages. This stage included multiple iterations of testing and refinement to improve both the hardware prototypes and the usability of the online platform.

Finally, the Evaluation phase assessed the effectiveness of both the toolkit and the prototypes. Through user testing, structured interviews, and feedback collection, insights were gathered on the usability, clarity, and functionality of the developed systems. This phase ensured that the toolkit met its intended purpose of bridging the gap between artistic creativity and wearable robotics, providing a foundation for future refinements.

By following this structured methodology, the project maintained an iterative and user-centered approach, allowing for adaptability and refinement at each stage of development.

3.1 Design Method

This project employs the Creative Technology Design Process as defined by Mader and Eggink (2014), which is segmented into four phases: ideation, specification, realisation, and evaluation. An illustrative figure of this process is included in Appendix A. This framework supports an iterative approach, allowing for continuous refinement based on user feedback, which is particularly beneficial during prototyping stages.

The participatory design approach was integral, involving the client, Jonathan Reus, throughout the product development cycle. This ensures the final product not only meets the user's needs but also incorporates their perspectives, enhancing the relevance and applicability of the wearable robotic masks.

3.2 Stakeholder Identification and Analysis

Stakeholder identification is a crucial process in design projects, ensuring that all relevant parties are considered in decision-making and project development. According to Freeman (1984), stakeholders are defined as any individual or group that can affect or be affected by the project's success. In this project, stakeholder identification began with discussions with Jonathan Reus, a key stakeholder, and was supplemented by brainstorming sessions to ensure a comprehensive understanding of the various individuals and groups involved.

The brainstorming method, as described by Osborn (1953), is a creative technique that fosters idea generation by encouraging free-flowing discussion without immediate critique. By using this approach, a broad spectrum of potential stakeholders was identified, including artists, engineers, educators, and members of the wearable robotics and performance art communities.

Once identified, stakeholders were analysed using the Influence vs. Interest matrix (figure 3.2), a widely used stakeholder management tool (Mendelow, 1991). This matrix categorizes stakeholders based on their level of influence (power) and level of interest, allowing for tailored engagement strategies.

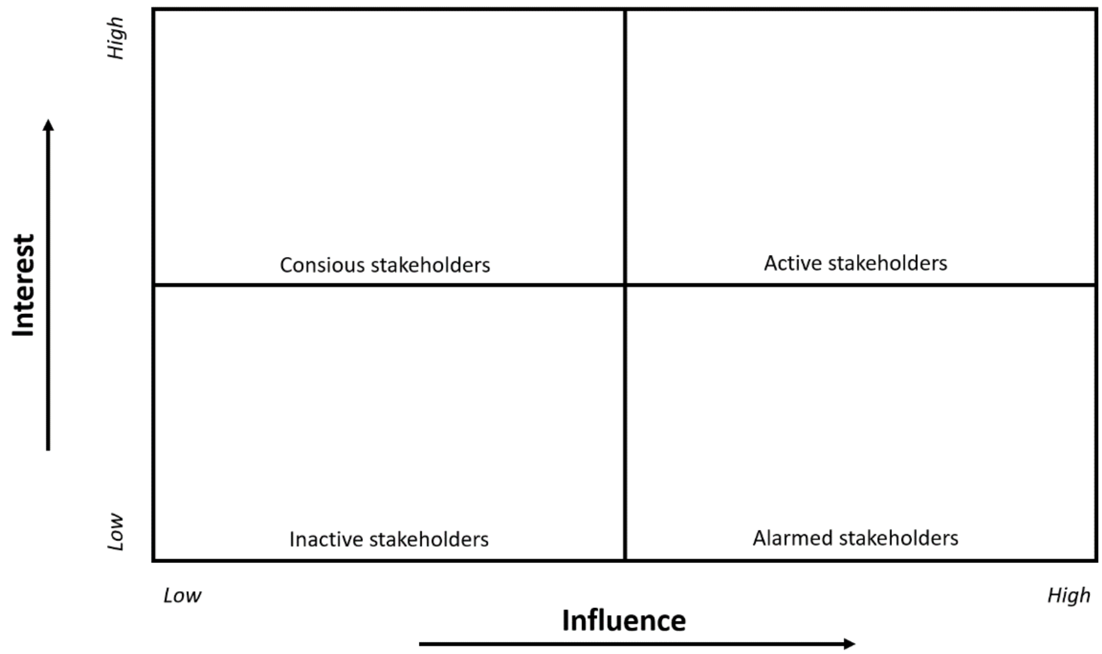

Figure 3.2 The Influence versus interest matrix used for stakeholder analysis.

In applying the Influence vs. Interest matrix to this project, stakeholders were categorised into four distinct groups:

1. **Inactive Stakeholders (Low Influence, Low Interest):** Also known as the 'crowd,' these stakeholders have minimal impact on the project's progression and outcome. They are not significantly affected by the project, nor do they have the power to influence it. While they are kept informed, extensive engagement with this group is not a priority.
2. **Conscious Stakeholders (Low Influence, High Interest):** These stakeholders, though lacking the power to effect changes, have a keen interest in the project's results. They can include end-users or community members who benefit from the project's success. Maintaining their interest and keeping them informed can turn them into project advocates, contributing to broader community support.
3. **Alarmed Stakeholders (High Influence, Low Interest):** Known as 'context setters,' these stakeholders possess the ability to impact the project significantly but may not have a direct interest in the daily progress or outcomes. They might include regulatory bodies or funding organisations. Their high influence means their requirements and expectations must be carefully managed, even if their interest in the project is not as pronounced.

4. **Active Stakeholders (High Influence, High Interest):** Referred to as 'players,' these are the most critical stakeholders. They have both a significant interest in and influence over the project. Active stakeholders typically include the project team, primary clients like Jonathan Reus, and key partners. Engaging with this group is essential for gathering requirements, obtaining feedback, and ensuring the project meets its objectives.

Using this framework, the project ensured that the appropriate stakeholders were involved at the necessary stages, with engagement strategies tailored to each group's characteristics. Figure 3.2 provides a visual representation of the Influence vs. Interest matrix applied in this project.

3.3 Requirements Elicitation and Prioritisation

Requirements elicitation is essential for defining the functional and non-functional needs of a system (Nuseibeh & Easterbrook, 2000). In this project, requirement gathering combined three methods: stakeholder interviews, desk research, and brainstorming sessions.

Once initial requirements were identified, the MoSCoW method (Agile Business, 2022) was used to prioritize them. This widely adopted approach helps teams focus on critical elements while ensuring that additional features can be added progressively.

- **Must Have:** These are the core functionalities essential for the project's success. Without them, the toolkit or the prototypes would fail to meet their primary objectives. For instance, the robotic mask required a motion system capable of expressive facial movements.
- **Should Have:** Important features that enhance usability and performance but are not immediately critical. An example is interactive tutorials on the toolkit websites, which improve accessibility but do not affect the core content.
- **Could Have:** Desirable but non-essential features that can be implemented later if time and resources allow. This category includes user-generated content submission for expanding the toolkit's resource pool.
- **Won't Have (For Now):** Features that were considered but deprioritized for this phase, either due to complexity or feasibility constraints. These might include live workshops or VR integration.

By using this method, the project ensured that development efforts remained aligned with key objectives while maintaining flexibility for future iterations.

3.4 Concept Ideation

The ideation phase of this project explored how wearable robotics could enhance artistic expression and transform identity perception. Ideation is a crucial step in the Creative Technology Design Process (Mader & Eggink, 2014) and is often guided by methodologies such as design thinking (Brown, 2009) and biomimetic inspiration (Vincent et al., 2006).

Brainstorming, as introduced by Osborn (1953) and refined by IDEO (2009), played a central role in generating concepts for wearable robotic devices. This technique encouraged divergent thinking, allowing for the exploration of multiple artistic and technological solutions.

Key inspirations included:

- The cultural and historical significance of masks, which informed the design of the robotic mask prototype, aiming to convey emotions dynamically.
- Motion systems in biomechanics, influencing the selection of four-bar linkages and soft robotics to create fluid, expressive movements.
- Prior works in wearable robotics, such as KOBAKANT and JIZAI ARMS, which emphasized the importance of customizability and interactive design.

This phase also shaped the structure of the toolkit websites, which were divided into artistic, technological, and educational themes based on the diverse needs of target users. Early wireframes and storyboards helped conceptualize how users would interact with the platform, ensuring intuitive navigation and engaging content delivery.

3.5 Product Specification

In this phase, user personas (Chang, Lim, & Stolterman, 2008) were crafted to represent potential users, defining their needs and behaviours. Interaction scenarios (Costa, 2020) followed, illustrating potential user interactions with the wearable robotic masks, identifying key user expectations and product interactions.

Functional and non-functional requirements were then detailed, covering essential functionalities and user experience factors like comfort and safety. These were prioritised using the MoSCoW method, categorising into Must have (essential features), Should have (important but not essential), Could have (desirable but non-essential), and Won't have (excluded features for the initial phase).

Finally, these requirements were translated into design blueprints through storylines and storyboards, visualising the intended user interactions and ensuring alignment across the development team. This approach streamlined the design process, ensuring a focused development aligned with user needs and project objectives.

3.6 Product Realisation

The realisation phase involved iterative development of the prototypes and toolkit websites. Prototypes such as the robotic mask and tentacle were constructed using materials like carbon rods, 3D-printed connectors, and lightweight Arduino-based systems for control and power. The toolkit websites were built using HTML, CSS, and Bootstrap, with each theme—artistic, technological, and educational—emphasizing tailored content and user experience.

Feedback loops played a critical role during this phase. The prototypes were continuously tested for functionality and comfort, providing insights that led to adjustments in motion mechanisms and design. Students evaluated the toolkit websites, suggesting improvements in navigation clarity and resource accessibility. These iterative refinements ensured that the final products met the diverse needs of their intended users.

3.7 User Evaluation Method

To evaluate the effectiveness of the prototypes and toolkit websites, a mixed-methods approach was adopted. Questionnaires provided quantitative data on usability, engagement, and clarity, while semi-structured interviews offered qualitative insights into user experiences and areas for improvement. Participants included artists, educators, and students, representing the primary user groups.

Evaluation criteria focused on three key areas: effectiveness, engagement, and accessibility. Effectiveness assessed how well the prototypes and websites fulfilled their intended purposes, such as enhancing artistic performances or conveying robotics concepts. Engagement measured user satisfaction with interactive features and thematic content. Accessibility evaluated the ease with which users could navigate the websites and apply the provided resources.

The feedback collected during this phase informed final adjustments to both the prototypes and toolkit websites, ensuring they were user-friendly, functional, and aligned with project objectives.

4. Ideation

This chapter outlines the project's ideation process, beginning with a rigorous assessment of stakeholder requirements and advancing towards the development of preliminary concepts. It documents the progression towards the final concept selection, a critical phase in this graduation project. This phase is characterized by a dual-pathway approach, balancing two fundamental aspects: the development of the artist's toolkit and the mechanical prototyping of wearable robotics mechanisms. These pathways are interconnected, with findings from one influencing the refinement of the other, as visualized in figure 4.1.

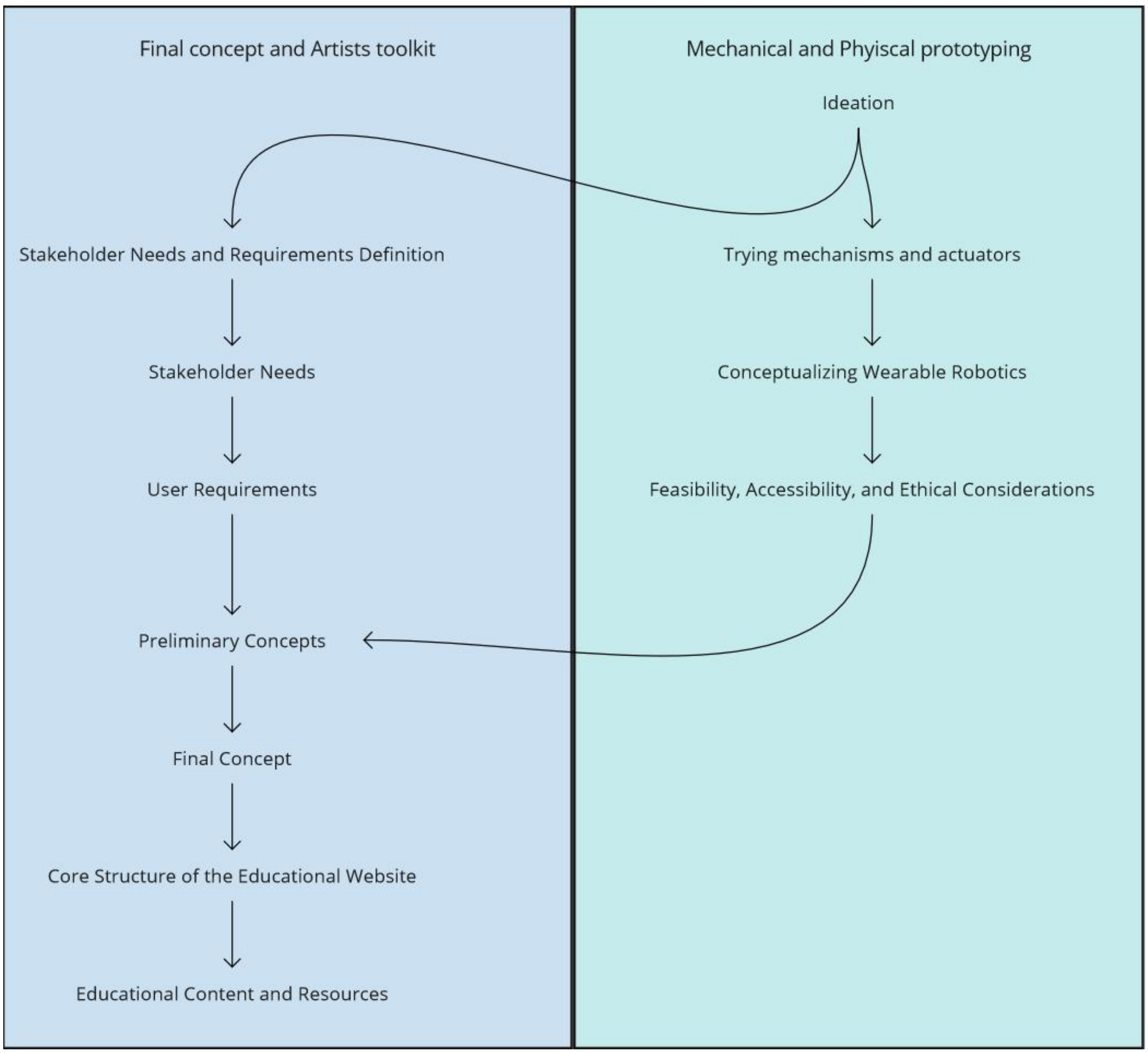

Figure 4.1: The Dual-Pathway Approach in the Ideation Phase, illustrating the simultaneous development of the artist's toolkit and the mechanical prototyping of wearable robotics.

On the left side of figure 4.1, the structured development of the artists' toolkit begins with an analysis of stakeholder needs, ensuring that the final resource aligns with the requirements of artists, technologists, and educators. These insights are distilled into user requirements that guide the conceptualization process, ultimately shaping the structure and content of the educational website. This systematic progression ensures that the toolkit is not only informative but also directly applicable to creative practitioners seeking to integrate robotic movement systems into their work.
Simultaneously, the right side of figure 4.1 outlines the mechanical and physical prototyping process, where wearable robotics concepts are explored through hands-on experimentation with actuators and movement mechanisms. This iterative process involves evaluating mechanical solutions in terms of their feasibility, accessibility, and ethical implications. Key considerations include ensuring comfort, safety, and artistic expressiveness in wearable designs.
The arrows in the diagram illustrate the interplay between these two processes. While the mechanical prototyping phase informs the toolkit by providing practical insights into motion systems and material constraints, the structured development of the educational resource helps translate these findings into accessible learning materials. The culmination of this parallel exploration is a comprehensive educational website designed to enable artists to incorporate wearable robotics into their work effectively.
By following this systematic dual-pathway approach, this chapter details the conceptual journey of the project, emphasizing the integration of technical innovation with artistic creativity within the scope of wearable technology. This iterative framework ensures that the final toolkit and prototypes not only serve as standalone contributions but also reinforce each other, offering a well-rounded resource for artists and technologists working at the intersection of robotics and performance art.

4.1 Stakeholder Needs and Requirements Definition

4.1.1 Stakeholder Identification and Analysis

Following the methodology outlined in Chapter 3, stakeholders for this project were identified and analysed based on their relevance to the fields of wearable robotics, artistic expression, and human-machine interaction (HMI). The identified stakeholders include:

- Active stakeholders
  - Primary artists who will directly use the wearable robotics
  - Online communities and platforms, such as Hackaday and Kobakant
- Alarmed stakeholders
  - People with knowledge that need inspiration (tinkerers, hackers)

- Conscious stakeholders
    - Artists with varying levels of technological expertise
    - Students interested in technology and art
- Inactive stakeholders
    - Secondary individuals interested in HMI

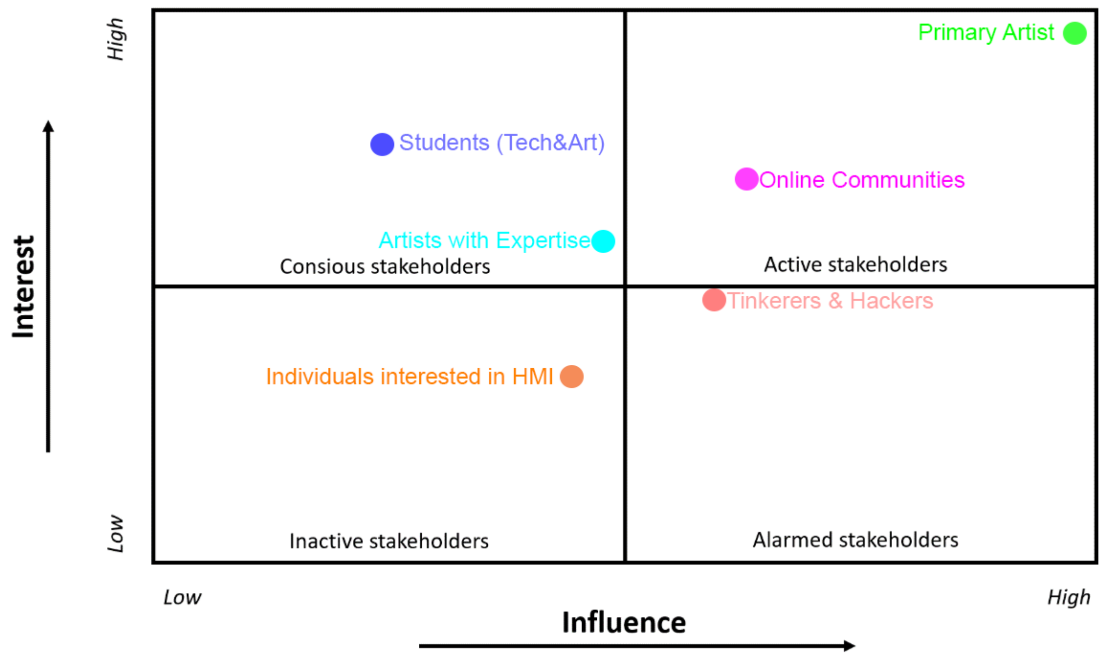

Figure 4.2: Interest versus influence grid with stakeholders.

An Influence vs. Interest grid, illustrated in figure 4.2, maps these stakeholders according to their impact and concern regarding the project. The detailed analysis of each stakeholder's interest and influence is summarised in table 4.1, explaining the rationale behind their placement on the grid.

Stakeholder	Analysis
People with Knowledge (Tinkerers, Hackers)	These individuals have a high interest in innovative projects combining technology and art. Their influence is moderate since they can provide valuable feedback and share knowledge but might not directly impact the project's outcome. Classified as conscious stakeholders, they are vital for inspirational feedback and community engagement.
Artists	This group is divided based on their technical knowledge: Technically Proficient Artists: High interest in integrating new technologies into their art but moderate influence on the project's technological aspects. They serve as active stakeholders, guiding the artistic direction. Non-Technical Artists: High interest in exploring new mediums but low influence on technical development. They are conscious stakeholders, impacting the project's accessibility and usability.
Students	Covering a broad range, from those studying art to those in technical fields: Tech-savvy Students: Moderate interest and influence, providing fresh insights and innovative ideas, making them conscious stakeholders. Non-Technical Students: High interest but low influence as they seek to learn; they are the conscious stakeholders for educational content.
Primary Artist	The main user and influencer of the project, with high interest and high influence, making them an active stakeholder. Their needs and feedback directly shape the project's development.
Individuals interested in HMI	They have a moderate to high interest but varying levels of influence, categorised as conscious to active stakeholders depending on their field and expertise.
Online Platforms (Hackaday, Kobakant)	Serve as critical mediums for dissemination and feedback, with high interest in showcasing innovative projects but moderate influence on the project's actual design, positioning them as conscious stakeholders.

Table 4.1: Analysis of the stakeholders highlights the diversity in their backgrounds, expectations, and contributions, guiding the prioritisation of their needs in the project development process.

4.1.2 Stakeholder Needs

Through a combination of interviews, workshops with stakeholders, and extensive literature research, we have pinpointed preliminary needs specific to our project's focus. These needs are fundamental in shaping the project's direction and are crucial in selecting the most appropriate and effective concept for development. Detailed in table 4.2, these requirements are instrumental in guiding the project towards fulfilling the expectations and requirements of its diverse stakeholders.

These requirements will play a pivotal role in the concept selection process, ensuring that the final product not only aligns with the technological and artistic vision of the project but also addresses the practical and operational needs of the stakeholders involved.

No.	Requirement	Source
1.	The final product must include a dedicated toolkit section for users to understand and apply wearable robotics and artistic concepts effectively.	(Soft Robotics Toolkit, 2023)
2.	The final product must provide a section for users to input projects and rectifications, fostering a collaborative and iterative development environment.	(madelinegannon, 2024)
3.	The platform must include a moderation system to ensure quality and relevance of content, with company involvement on a case-by-case basis to maintain a balance between guidance and user independence.	(Soft Robotics Toolkit, 2023)
4.	The final product must remain open source, ensuring accessibility and encouraging a wide range of contributions and iterations from the community.	(Revolutionizing Wearable Robotics through Open-Source Innovation, 2025)
5.	The toolkit should cater to both technical and non-technical users, encompassing a wide range of skills and knowledge levels.	(Soft Robotics Toolkit, 2023)
6.	The final product must facilitate easy project input and modification by users, supporting continuous improvement and adaptability.	(madelinegannon, 2024)

Table 4.2: Preliminary stakeholder needs.

4.2 User Requirements

Building on the identified stakeholder needs, this section delineates the user requirements essential for the development of the final product. These requirements are derived from the preliminary stakeholder needs, ensuring that the product will serve the intended audience effectively and fulfil the project's objectives. They represent the specific expectations from various user groups and form the basis for the design and development of the wearable robotics toolkit.

No.	User Requirement	Rationale
1.	The platform must be accessible online, with a user-friendly interface suitable for a diverse range of users, from artists to technologists.	Ensures wide accessibility and usability across different user groups.
2.	The toolkit must provide comprehensive guidance and resources for both technical and artistic development, accommodating users with varying levels of expertise.	Facilitates learning and experimentation among users with diverse backgrounds.
3.	Users must be able to submit their own projects and suggest modifications to existing ones, encouraging a participative and collaborative environment.	Promotes user engagement and collective knowledge building.
4.	A moderation system should be implemented to ensure the quality and relevance of user-contributed content, maintaining the platform's integrity and usefulness.	Ensures the platform remains a credible and valuable resource for all users.
5.	The platform and all contributed content must be transparent: i.e. remain open source, promoting transparency, accessibility, and community-driven development.	Encourages innovation and broadens the scope of user contributions and collaboration.
6.	The toolkit should include features that allow for easy adaptation and customization by users, supporting a wide range of artistic and technical projects.	Enables users to tailor the platform to their specific needs and projects.
7.	Content and tutorials within the toolkit should avoid technical jargon, or when necessary, provide clear explanations, making the platform accessible to non-technical users.	Reduces barriers to entry for users new to wearable robotics or technical subjects.
8.	The final product must support multilingual content, ensuring accessibility to a global user base, starting with English, and including options for additional languages based on user demographics.	Expands the reach and inclusivity of the platform to non-English speaking users.

Table 4.3: User requirements.

These user requirements will guide the development process, ensuring the final product is aligned with the needs and expectations of our diverse user base. They serve as the foundation for the upcoming design and prototyping phases, where these requirements will be translated into concrete features and functionalities of the wearable robotics toolkit.

4.3 Preliminary Concepts

The ideation process synthesized theoretical insights and practical challenges to identify innovative yet accessible solutions for wearable robotics in artistic applications. Building upon the original concepts explored earlier in this chat, the process evolved to focus on practical and impactful designs for both prototypes and toolkit websites.

4.3.1 Original Ideas as a Foundation

The ideation phase began as an individual brainstorming process, where concepts were systematically explored through written lists that categorized potential wearable robotics applications in performance art. These lists evolved over multiple iterations, integrating insights from literature, prior research, and reflections on relevant artistic and technological precedents.
The early stage of brainstorming involved identifying key artistic and mechanical principles that could be incorporated into wearable robotics. These initial ideas were not generated in isolation but were refined through ongoing discussions with the project supervisor and client, ensuring alignment with both artistic and practical objectives. The brainstorming process primarily focused on the following key areas:

- **Artistic Expression & Storytelling:** How could wearable robotics expand performative storytelling?
- **Mechanical Feasibility:** What movement systems could be realistically integrated into wearable formats?
- **Toolkit Usability**: How could artists and technologists access and apply these concepts?

One of the first major conceptual ideas to emerge was a robotic mask inspired by Tim Hawkinson's "Emoter," which explored wire-linked mechanisms to create dynamic facial expressions. This concept emphasized the role of movement in shaping identity perception, forming the basis of the toolkit's primary use case.
Another major outcome was the wearable tentacle prototype, designed for fluid, natural movements in performance settings. This idea stemmed from reflections on organic motion and its relationship to stage presence, leading to explorations of different mechanical systems such as soft robotics and tendon-driven actuation.
Beyond individual prototypes, early brainstorming sessions also considered how knowledge on wearable robotics could be effectively shared. The idea of a collaborative, open-access toolkit was inspired by platforms like Hackaday and Kobakant, with the goal of creating a resource hub for artists and technologists. This vision later materialized into the three-pronged website structure, tailored to different levels of expertise.

While no traditional sketches or mind maps were created during the ideation phase, written lists detailing potential movement systems, control methods, and aesthetic applications were reviewed and iterated upon in discussions with the supervisor and client. These discussions helped refine the concepts that would later undergo technical feasibility testing in subsequent phases of the project.

4.3.2 Transition to Current Prototypes

Through iterative refinement, the initial concepts were developed into the following key prototypes:

- **Wearable Tentacle**: Constructed using carbon rods and a winch system, this prototype facilitates fluid, natural movements, making it ideal for abstract performances and dynamic storytelling.
- **Robotic Mask**: A mask equipped with wire-linked mechanisms to dynamically express emotions, drawing inspiration from artistic works such as Hawkinson's "Emoter."
- **Linear Actuator with Syringe Connector**: This prototype enables precise pneumatic or low-pressure hydraulic motion, suitable for creating subtle yet impactful movements in artistic projects.
- **Rack-and-Pinion Mechanism**: A sinusoidal movement system designed for synchronized performances, offering precision and repeatability.
- **Four-Bar Linkage**: A periodic movement system capable of generating rhythmic and synchronized actions, perfect for choreographed displays or performances.

To complement these main prototypes, two supporting prototypes were developed:

- **GoPro-Style Mount**: A 3D-printed attachment system providing an easy platform for testing and integrating wearable robotics components.
- **Electronics Backpack**: A wearable Arduino and battery pack system designed for easy customization and programming, allowing artists to experiment with diverse robotic movements.

These prototypes were selected based on their feasibility, artistic potential, and ability to demonstrate the interplay between robotics and creative expression. Together, they form a versatile toolkit for exploring wearable robotics in artistic contexts.

4.3.3 Toolkit Website Development

In parallel with prototype development, the toolkit websites were conceptualized to provide a structured platform for artists and technologists. Divided into artistic, technological, and educational themes, the websites were designed to cater to a diverse audience, offering tailored resources for different user needs.

Key features of the toolkit websites include:

- **Step-by-Step Tutorials**: Detailed guides for assembling prototypes like the wearable tentacle or robotic mask, ensuring accessibility for users with varying levels of expertise.
- **Downloadable Resources**: CAD files, materials lists, and code snippets to facilitate easy replication and adaptation of prototypes.

- **Case Studies**: Real-world examples showcasing wearable robotics in artistic applications, offering inspiration and practical insights.

By combining comprehensive educational content with practical tools, the toolkit websites serve as both an instructional resource and a creative springboard. They ensure accessibility for beginners while providing depth for advanced users, empowering artists to explore and innovate at the intersection of art and technology.

4.4 Final Concept

After synthesizing feedback and evaluating preliminary concepts, the final concept integrates the wearable prototypes with the toolkit websites, creating a holistic system for artistic exploration with wearable robotics. Inspired by sites like Kobakant and Hackaday, this integration ensures that artists, technologists, and educators have access to practical resources, creative inspiration, and technical guidance. The basic version of each of the three websites will be inspired by the sketch seen in figure 4.3.

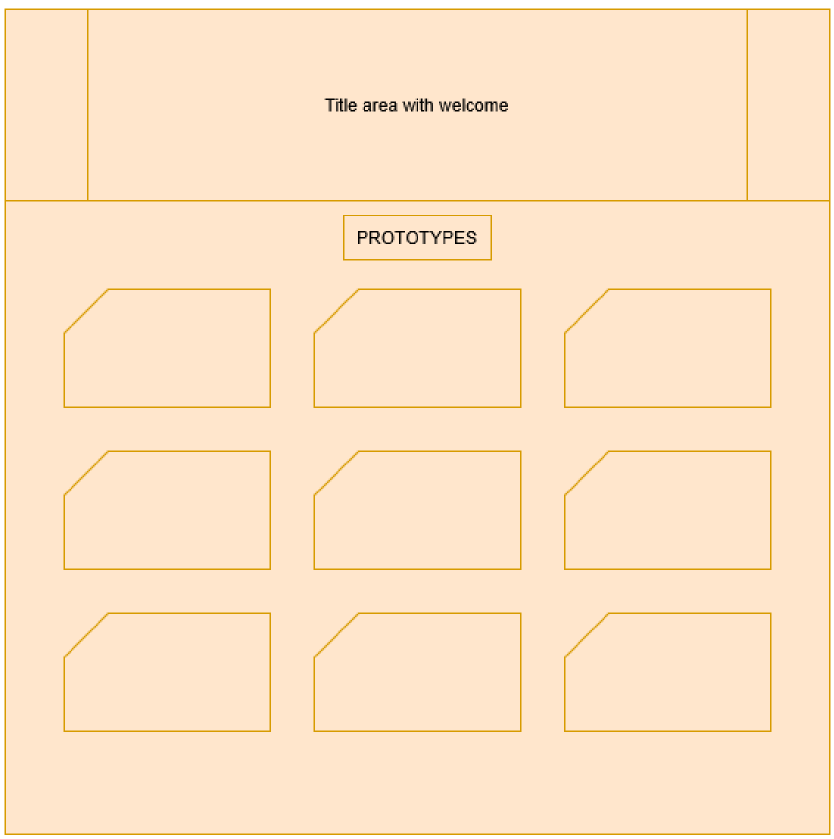

Figure 4.3: Sketch of final concept website.

4.4.1 Core Structure of the Educational Website

The toolkit websites are designed as comprehensive platforms tailored to different user needs, organized into three distinct versions: Artistic, Technological, and Educational. Each version provides specialized resources while maintaining a cohesive structure across the toolkit. Key features include:

- **Introductory Guides**: Simplified explanations of wearable robotics principles, tailored for non-technical audiences to ensure accessibility.
- **Step-by-Step Tutorials**: Detailed instructions for creating prototypes, including the wearable tentacle, robotic mask, linear actuator with syringe connector, rack-and-pinion mechanism, and four-bar linkage. These tutorials focus on using accessible materials and tools.
- **Downloadable Resources**: CAD files, materials lists, and example code to enable users to replicate and adapt prototypes.
- **Case Studies**: Real-world examples of wearable robotics applied in artistic settings, showcasing creative and innovative uses of the prototypes.
- **Interactive Features**: Spaces for users to share their projects, provide feedback, and collaborate, fostering a sense of community and collective knowledge-building.
- **Ethical Considerations**: Dedicated sections discussing sustainability, responsible material use, and the ethical implications of wearable robotics in art and performance.

It is important to clarify that not the entirety of the above-mentioned core structure will be functional and completed in this project. To accurately evaluate the final concept some of the key features like the interactivity will be simulated using non-functional placeholders like a fake “Share” button.

4.4.2 Accessibility, Inclusivity and Scalability

The websites are designed with accessibility, inclusivity, and scalability as core principles. Clear, jargon-free language ensures that users from diverse backgrounds—including non-technical and beginner audiences—can easily engage with the content. Efforts to create a welcoming platform extend to ensuring that prototypes and tutorials accommodate individuals with varying physical and technical capabilities. For instance, guidance on assembling prototypes emphasizes ease of use and encourages adaptations for diverse needs.

The platform’s open-source framework is instrumental in fostering collaboration and adaptability. By allowing users to contribute improvements, translations, and additional resources, the toolkit evolves organically to meet the demands of a growing and diverse audience. The potential for multilingual support ensures that the platform reaches a global user base, extending its impact far beyond its initial implementation.

4.4.3 Conclusion

The ideation process successfully translated initial concepts into tangible prototypes and a structured toolkit, ensuring that wearable robotics can serve as a foundation for artistic expression. Rather than providing rigid, pre-defined solutions, the chosen mechanisms—such as the wearable tentacle, robotic mask, and four-bar linkage—were deliberately kept simple. This allows artists to retain creative control, adapting and expanding upon these movement systems to suit their own artistic visions.

A key focus was ensuring that the prototypes were clearly presented, emphasizing their motion capabilities rather than the underlying technical details of the website. By showcasing fundamental movement principles in an accessible way, the toolkit enables artists to analyse and recreate the mechanics behind robotic systems they encounter in performances or installations. Whether an artist is inspired by fluid organic motion, expressive facial changes, or rhythmic mechanical movements, the toolkit provides an entry point for understanding and experimenting with these techniques.

The final concept balances artistic freedom with technical clarity, offering a resource that does not dictate artistic choices but instead provides a structured yet open-ended foundation. By keeping mechanisms straightforward and adaptable, the project ensures that wearable robotics can seamlessly integrate into various creative practices, fostering new approaches to movement and identity transformation in performance art.

5. Specification

This chapter outlines the detailed specifications for the educational website and the wearable robotics prototypes. It builds on the conceptual groundwork established in the ideation phase and refines the preliminary ideas into concrete functional and non-functional requirements. This phase corresponds to the "Specification" stage of the Creative Technology Design Process (as detailed in Chapter 3), where the preferred concept is structured into a well-defined product through iterative refinement and stakeholder validation.

The specification phase is crucial in ensuring that both the physical prototypes and the toolkit website are designed to meet user needs effectively. The chapter begins with an evaluation of stakeholder feedback, which played a vital role in refining the final concept. The selected wearable robotics mechanisms are presented, followed by a breakdown of the website's structure and interactive features. Then, the chapter defines the functional and non-functional requirements, ensuring usability, accessibility, and performance. Finally, the system requirements establish the technical foundations necessary to develop a scalable and sustainable platform.

5.1 From Physical Prototypes to the Toolkit Website

The transition from physical prototypes to an educational website is a structured process that ensures accessibility and usability for artists and technologists. The physical prototyping phase involved testing various movement systems—such as the robotic mask, wearable tentacle, and four-bar linkage—to assess their artistic and practical applications. These prototypes provided fundamental insights into motion principles, which were then translated into educational resources.

The website serves as a bridge between the technical knowledge gained from physical prototyping and the artistic freedom of its users. Instead of focusing on rigid technical details, the platform highlights the core motion principles behind each prototype, allowing users to understand, adapt, and innovate upon them in their own projects. The website is structured to offer tutorials, downloadable resources, and interactive tools that guide artists through the process of implementing wearable robotics in performance art. In this way, the website does not just document the prototypes but transforms them into an evolving toolkit that supports creative and technical experimentation.

5.2 Evaluation of Concept with Stakeholders

5.1.1 Stakeholder Feedback and Refinement

Following the presentation of preliminary concepts, stakeholders including artists, technologists, and educators provided valuable insights into the practical and educational applications of wearable robotics. Their feedback emphasized the importance of:

- Ensuring accessibility for both technical and non-technical users.
- Highlighting mechanisms that are both innovative and practical for artistic applications.
- Developing a toolkit website with intuitive navigation and clear educational content.

- Addressing ethical considerations in wearable robotics, such as sustainability and inclusivity.

During this phase, new insights were gained that influenced the refinement of the preferred concept. Iterations and stakeholder validation ensured the updated concept met the needs of the target audience while remaining feasible for implementation.

5.1.2 Final Mechanisms to Pursue

Based on stakeholder feedback and educational goals, the following mechanisms were selected for detailed exploration and instruction:

- **Wearable Tentacle**: Using carbon rods and a winch system, this mechanism was chosen for its ability to create lifelike, fluid movements that inspire storytelling and abstract artistic performances.
- **Robotic Mask with Emoter Mechanism**: Leveraging wire-linked systems, this prototype focuses on conveying emotional expressions, enhancing the integration of robotics and human identity in performance art.
- **Linear Actuator with Syringe Connector**: Ideal for creating precise pneumatic or low-pressure hydraulic movements, enabling intricate and controlled actions in wearable art.
- **Rack-and-Pinion Mechanism**: Providing sinusoidal motion for synchronized artistic effects.
- **Four-Bar Linkage**: A system enabling periodic, rhythmic movements, suitable for dynamic choreography.

These mechanisms form the core instructional content on the toolkit website, supported by multimedia resources such as videos, CAD files, and interactive tutorials.

5.2 Functional Diagram

The transition from physical prototypes to the digital toolkit is central to the project's structure. The mechanisms developed during prototyping—including the wearable tentacle, robotic mask, and motion systems—serve as the foundation for the toolkit’s instructional content. By translating these physical designs into structured educational resources, the toolkit ensures that users, whether artists or technologists, can engage with wearable robotics concepts without needing direct access to the prototypes. This transformation enables a broader audience to experiment with movement systems, fostering creative exploration beyond the initial designs.

The educational website integrates several key functionalities, as illustrated in the functional diagram (figure 5.1) The platform’s main functions are divided into four color-coded categories, each representing a distinct area of user interaction:

- **Educational Content (Yellow):** Includes tutorials, case studies, and a glossary to provide users with theoretical and practical insights. These resources ensure that users with varying levels of expertise—from beginners to advanced practitioners—can engage with the content effectively.
- **Interactive Features (Green):** Comprises tools such as the design and prototype module and the project sandbox, which allow users to visualize, plan, and experiment with their

wearable robotics projects. These elements encourage hands-on engagement and iterative development.

- **Community Engagement (Purple):** Encompasses forums, user profiles, and feedback mechanisms to facilitate knowledge sharing and collaboration. By integrating these social features, the platform fosters a dynamic community where users can learn from each other's experiences.
- **Resource Management (Pink):** Covers the technical infrastructure, including the content management system (CMS), user management tools, and data analytics, ensuring the platform's stability, scalability, and ease of maintenance.

By structuring the platform around these core functionalities, the website ensures a balanced integration of theoretical knowledge, practical application, and community-driven learning, making wearable robotics more accessible and adaptable to diverse artistic and technological pursuits.

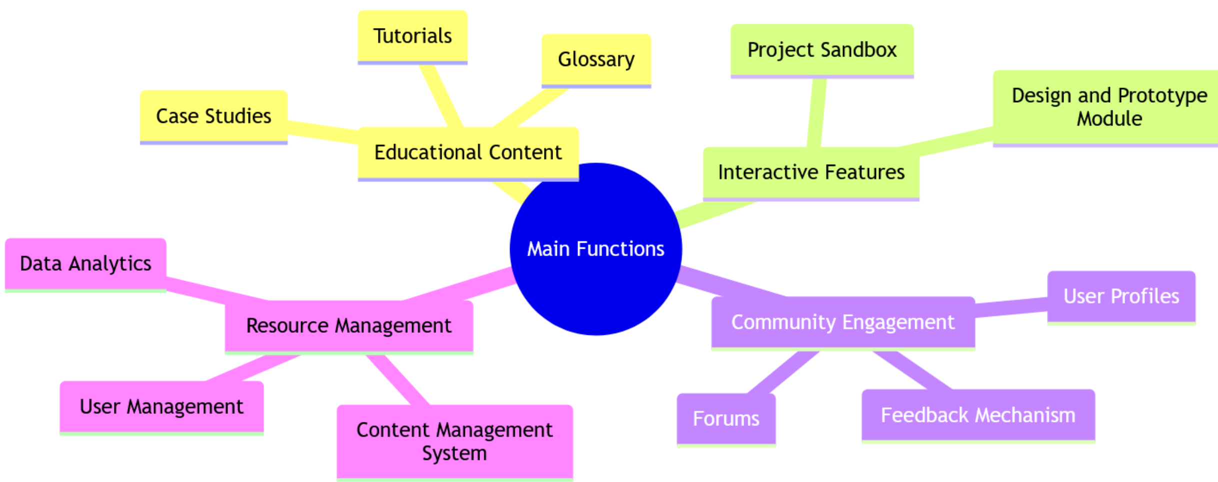

Figure 5.1 Functional diagram divided per category of user interaction.

5.3 Activity Diagram

The user journey through the website follows the structured workflow outlined in the activity diagram (figure 5.2). This step-by-step process ensures that users can effectively engage with the educational content, participate in community interactions, and apply their knowledge to create wearable robotics projects.

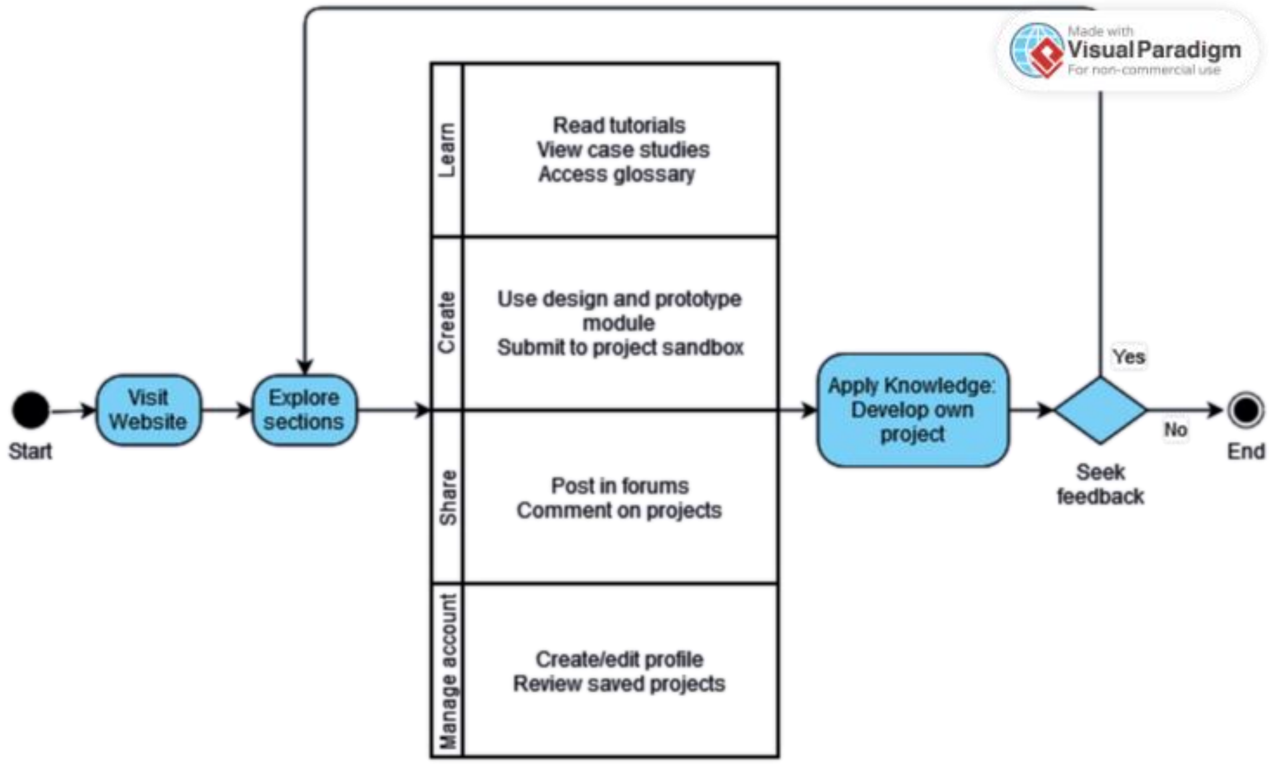

Figure 5.2: Activity diagram of toolkit website.

To clarify this process, a cognitive walkthrough is provided, detailing how a user would navigate the platform:

1. Visit Website:
    a. The journey begins when a user visits the platform, arriving at the homepage where they can explore available resources.
2. Explore Sections:
    a. The user is then guided to explore different sections of the website, where they can choose between the Artistic, Technological, or Educational toolkit versions depending on their interests and expertise.
3. Learning Phase:
    a. Users seeking foundational knowledge first enter the Learn section, where they can:
        i. Read tutorials about wearable robotics concepts.
        ii. View case studies showcasing real-world applications.
        iii. Access a glossary explaining key terms in an accessible, jargon-free manner.
    b. This phase is particularly important for newcomers or non-technical users, ensuring they gain a strong conceptual understanding before engaging with more advanced content.

4. Creation Phase:
    a. After acquiring foundational knowledge, users can proceed to the Create section, where they:
        i. Utilize the design and prototype module to start developing their own projects.
        ii. Submit their work to the project sandbox, an interactive space where they can refine their ideas with the community's help.
    b. This phase is crucial for hands-on learning, allowing users to transition from theory to practice by working with CAD files, movement systems, and step-by-step guides.
5. Sharing and Community Engagement:
    a. Users then move to the Share section, which fosters collaboration by enabling them to:
        i. Post their projects and insights in forums.
        ii. Comment on other users' projects, offering feedback and suggestions.
    b. This step is integral to knowledge exchange, encouraging discussions between artists, engineers, and educators.
6. Managing Accounts and Personalization:
    a. Users have the option to personalize their experience in the Manage Account section, where they can:
        i. Create and edit their profile.
        ii. Review saved projects for future iterations.
    b. This ensures a customized learning experience, allowing users to track their progress.
7. Applying Knowledge – Developing Projects:
    a. With sufficient learning and community support, users apply their knowledge by developing their own wearable robotics projects.
    b. At this stage, users can either complete their project independently or seek further feedback before finalizing their work.
8. Feedback Loop and Project Completion:
    a. If additional refinement is needed, users seek feedback, returning to earlier phases like the forums or project sandbox to iterate on their designs.
    b. Once satisfied, they finalize their project, marking the successful completion of the workflow.

By guiding users through this structured process, the toolkit effectively bridges the gap between theoretical knowledge and hands-on application, ensuring that artists, technologists, and educators can fully leverage wearable robotics in their creative practice.

5.4 Requirements

Defining the technical, content, and user experience requirements necessary for the website.

5.4.1 Functional Requirements

Functional requirements focus on the specific behaviours and operations of the website and toolkit. The platform includes a content management system (CMS) to facilitate the efficient publishing and updating of educational materials. A robust search functionality enables users to find content tailored to their interests and skill levels. User registration and profiles allow for personalization, such as saving content and tracking progress. Interactive tools like the design and prototype module and the project sandbox promote active engagement and collaboration. Community features, including forums and feedback channels, foster a collaborative environment. Finally, open-source transparency ensures that the platform remains accessible and encourages community-driven contributions. All of these are ranked using the MoSCoW method in table 5.1.

No.	Requirement	Must	Should	Could	Won't
1	The platform must be accessible online for users to engage with the toolkit.	X			
2	The interface must be user-friendly for both artists and technologists.	X			
3	The website must provide comprehensive guidance on both technical and artistic development.	X			
4	The platform must be open-source to ensure accessibility and community-driven contributions.	X			
5	The website should be hosted on a reliable platform with robust security measures.		X		
6	The website should ensure compatibility across different devices and browsers.		X		
7	Users should be able to submit projects and propose modifications, contributing to an iterative and evolving knowledge base.		X		
8	The content should be clear, jargon-free, and supplemented with explanations when necessary.		X		
9	The toolkit should allow for easy adaptation and customization, supporting a wide range of users.		X		
10	The platform could include search functionality to help users find relevant content by interest and skill level.			X	
11	A moderation system could ensure the quality and relevance of user-contributed content.			X	
12	The toolkit could support multilingual content, with English as the primary language.			X	
13	Additional language options could be implemented based on user demographics.				X
14	The platform could include a Content Management System (CMS) for easy publishing and updates.				X
15	User registration and profile creation could be included for saving progress and tracking engagement.				X

Table 5.1: Functional requirements of toolkit/website.

5.4.2 Non-functional Requirements

Non-functional requirements (NFRs) define the quality attributes of the platform, ensuring that the system is usable, efficient, secure, and maintainable. These requirements shape the user experience by determining how smoothly the website operates and how accessible it is across different user groups. While functional requirements outline what the system does, non-functional requirements focus on how it performs those functions.

In this project, NFRs ensure that the toolkit remains intuitive for both technical and non-technical users, runs efficiently on various devices, and maintains high content quality. Additionally, considerations such as load times, ease of navigation, and accessibility are crucial for a seamless user experience. While some aspects of usability may overlap with functional requirements, NFRs explicitly define the performance expectations and constraints for the system.

No.	Non-Functional Requirement	Must	Should	Could	Won't
1	The interface must be intuitive and user-friendly, ensuring ease of use for diverse user groups.	X			
2	The platform must present information in a structured and accessible manner, supporting users of all skill levels.	X			
3	All content must be clear, understandable, and jargon-free, with explanations where necessary.	X			
4	The website must implement secure hosting with HTTPS encryption to protect user data and ensure high availability.	X			
5	The website should have a simple and predictable navigation structure to improve accessibility.		X		
6	Users should perceive content as high quality and relevant, ensuring a positive user experience.		X		
7	The website should load within three seconds on standard internet connections for optimal performance.		X		
8	The platform should maintain compatibility with all major browsers and devices, ensuring accessibility across technologies.		X		

Table 5.2: Non-functional requirements of toolkit/website.

6. Realization

This chapter outlines the implementation of both the wearable robotics prototypes and the educational website. It follows the Realization phase of the Creative Technology Design Process, detailing the transition from conceptual designs to functional implementations. Given the dual nature of the project, this chapter is divided into two sections:

- **Section 6.1:** Prototyping the Wearable Robotics Mechanisms — Covering the physical development, material selection, and iterative refinement of prototypes such as the robotic mask, wearable tentacle, and other movement systems.
- **Section 6.2:** Developing the website — Covering the creation of the three toolkit versions (Artistic, Technological, Educational), including their structure, visual design, and interactive features.

6.1 Prototyping the Wearable Robotics Mechanisms

This section focuses on the development, testing, and refinement of the wearable robotics prototypes. Each mechanism was designed to serve as a modular, adaptable tool for artists, allowing them to explore robotic movement in performance art without being constrained by predefined artistic styles. The five primary prototypes were selected for their diverse motion capabilities, and two additional supporting prototypes were developed to explore experimental applications.

The prototyping process followed three guiding principles:

1. **Simplicity and Adaptability**: The mechanisms were intentionally kept basic, allowing artists to modify or combine them creatively.
2. **Exploratory Learning**: Each prototype demonstrates a specific movement system that users can apply to their projects.
3. **Physical and Digital Integration:** The prototypes are complemented by the educational website, which provides guides, CAD files, and explanations for artists and engineers alike.

6.1.1 Transition from Concept to Functional Prototype

The transition from concept sketches to functional prototypes was iterative, involving multiple design refinements based on stakeholder feedback, movement testing, and material selection.

- **Stakeholder Input:** Artists and engineers emphasized the importance of modular, adaptable mechanisms rather than rigid, pre-programmed systems.
- **Material Selection:** Components such as carbon rods, flexible polymers, and wire-linked parts were chosen for their balance between durability and artistic fluidity.
- **Mechanical Refinements:** Movement inconsistencies in early prototypes (such as stiffness in the robotic mask and misalignment in the rack-and-pinion system) were corrected through component adjustments and alternative material testing.

Each prototype was tested both mechanically and artistically, ensuring that movements were smooth, expressive, and easy to control.

6.1.2 Development Stages

All prototypes followed a structured four-stage development cycle:

1. **Conceptualization:** Sketching and CAD modelling of movement principles.
2. **Material Selection & Testing:** Evaluating materials for flexibility, strength, and ease of control.
3. **Prototyping & Iteration:** Assembling functional models and refining them through performance testing.
4. **Final Assembly & Calibration:** Fine-tuning movements to align with both artistic and mechanical requirements.

6.1.3 The Five Primary Prototypes

Each prototype represents a different movement system, allowing artists to experiment with distinct robotic behaviours.

1. Wearable Tentacle

- **Motion Type:** Fluid, organic movement using a winch-based system.
- **Design:** Made of carbon rods, controlled by a motorized winch that contracts and relaxes tension to create lifelike motion.
- **Use Case:** Designed for abstract performances and storytelling, where expressive and unpredictable motion enhances stage presence.
- **Challenges & Refinements:**
    - Early iterations had uneven movement due to tension inconsistencies in the cable system.
    - Adjusting the winch spool diameter and adding a guiding mechanism improved control.

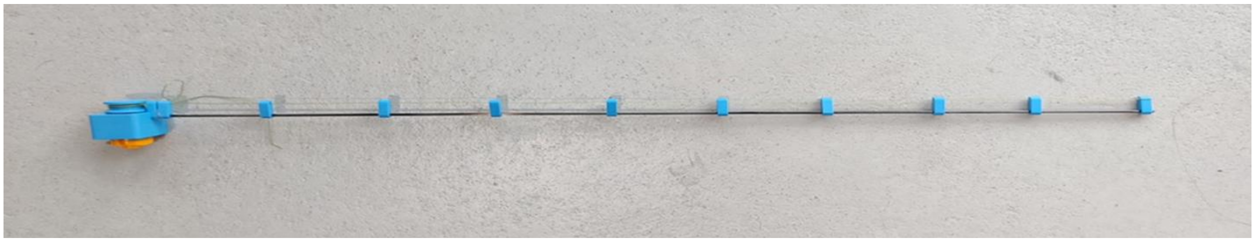

Figure 6.0.1: Wearable tentacle from carbon rod and 3D-printed parts.

2. Robotic Mask (with Emoter Mechanism)

- **Motion Type:** Expressive facial movement using wire-linked actuation.
- **Design:** Inspired by Tim Hawkinson's "Emoter", this mask features wire-linked components that move with servo motors to alter expressions.
- **Use Case:** Created for performance artists exploring facial identity and emotion through robotic augmentation.
- **Challenges & Refinements:**
  - Initial designs were too rigid, limiting expressiveness.
  - Switching to thinner wire and adjusting pivot points resulted in smoother transitions between expressions.

Figure 6.2: Tim Hawkinson inspired robotic mask.

3. Linear Actuator with Syringe Connector

- **Motion Type:** Pneumatic or hydraulic-based linear extension and contraction.
- **Design:** Uses a syringe-driven actuator, controlled through pressure differentials, creating smooth, controlled motion.
- **Use Case:** Ideal for deliberate, precise movements, such as theatrical gestures or slow, controlled expansions of body-mounted components.
- **Challenges & Refinements:**
  - Early versions leaked air, leading to inconsistent force output.
  - Switching to reinforced syringes with tighter seals improved reliability.

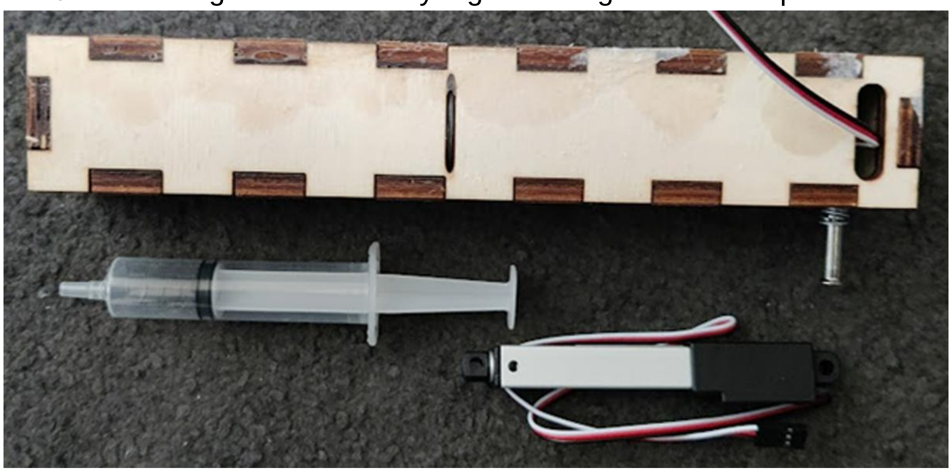

Figure 6.3: Syringe (left) and linear actuator (right) and the casing in which they are housed.

4. Rack-and-Pinion System

- **Motion Type:** Rhythmic, sinusoidal motion using geared mechanical movement.
- **Design:** A 3D-printed rack-and-pinion system generates repetitive linear motion.
- **Use Case:** Suitable for mechanized choreography, enabling artists to integrate mechanical rhythms into performances.
- **Challenges & Refinements:**
  - The initial gear alignment caused slippage, disrupting the motion cycle.
  - Increasing tooth engagement and refining the gear mesh corrected these inconsistencies.

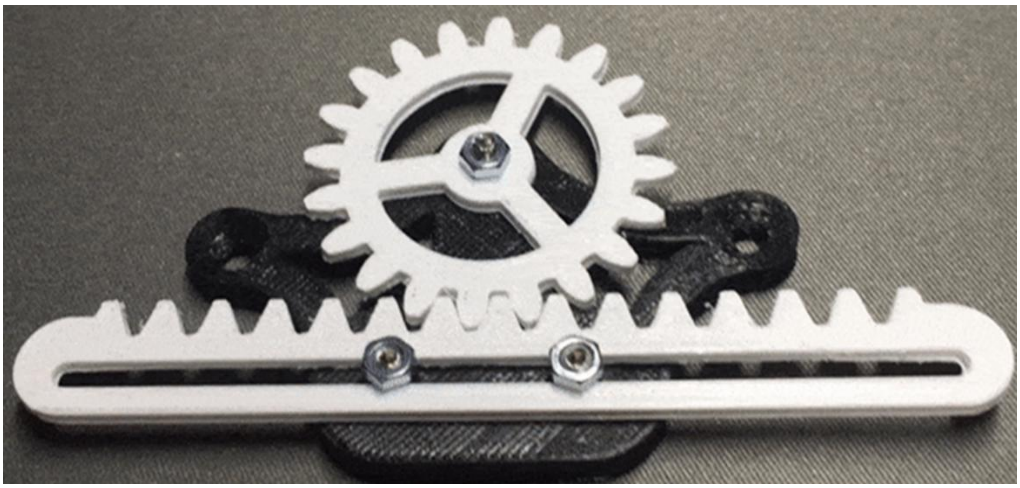

Figure 6.4: Simple 3D-printed rack-and-pinion system.

5. Four-Bar Linkage

- **Motion Type:** Cyclical, repeated movement through a pivoting arm system.
- **Design:** Uses four interconnected bars to generate predictable, repetitive motion.
- **Use Case:** Designed for synchronized performances, where automated movement patterns enhance dance or interactive stage elements.
- **Challenges & Refinements:**
  - The first version had unbalanced motion, causing jerkiness.
  - Adjusting pivot distances and joint tolerances resulted in fluid, natural movement.

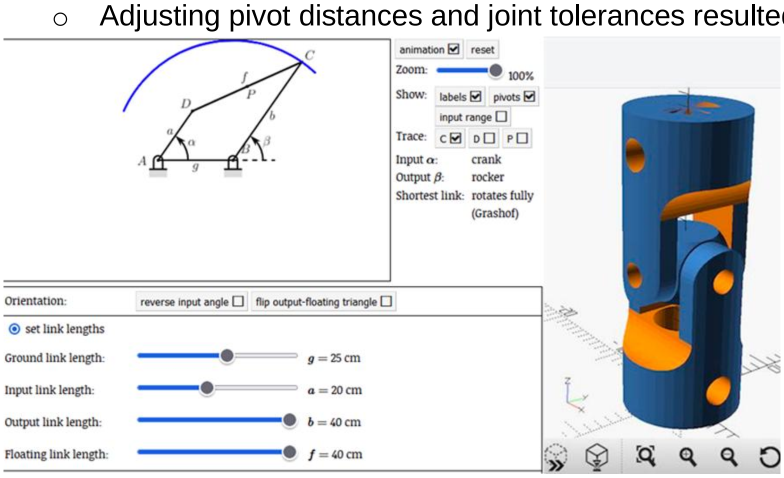

Figure 6.5: Components and configuration of four-bar linkage.

6.1.4 Supporting Prototypes

In addition to the five primary mechanisms, two supporting prototypes were developed to enhance usability and experimentation.

1. GoPro Attachments

- **Purpose:** A modular mounting system allowing artists to make any mechanism wearable.
- **Design:** Small 3D-printed brackets attach to the tentacle and mask, providing easy mounting options for headwear.
- **Use Case:** Enables artists to easily mount any desired mechanism in any desired position.

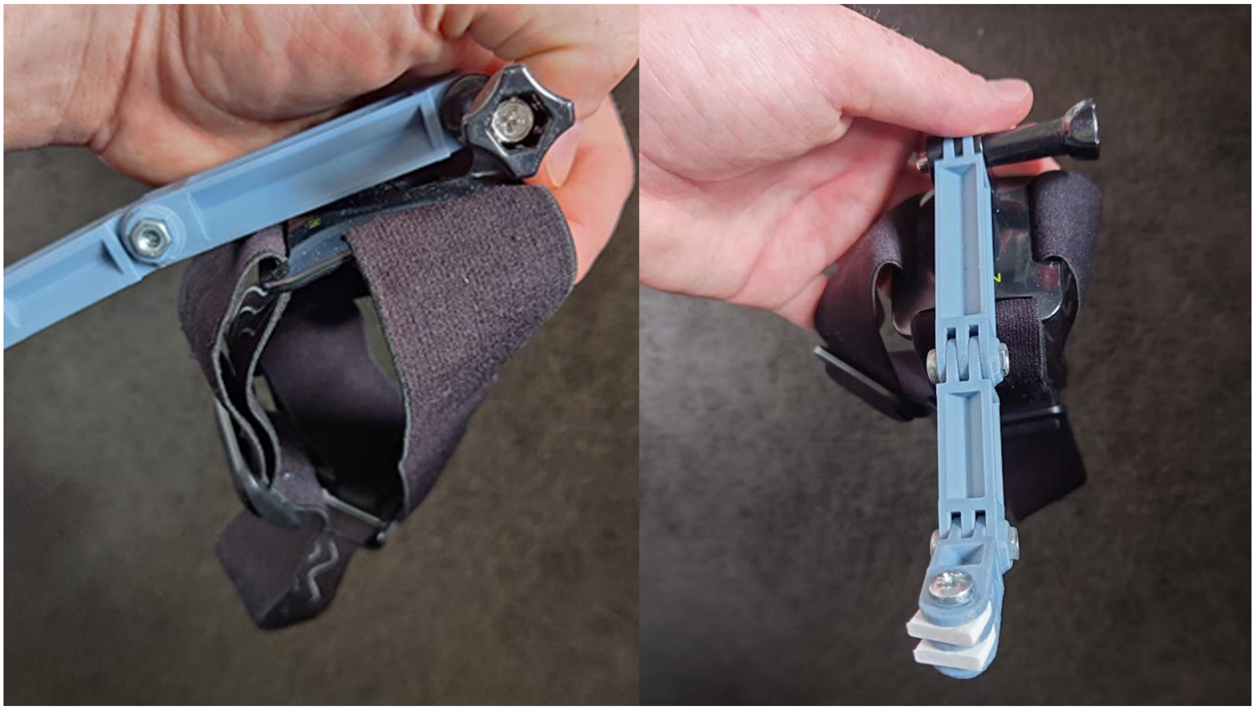

Figure 6.6: A GoPro head strap and the extension pieces mounted.

6.1.4.2 Arduino Backpack

- **Purpose:** A wearable microcontroller hub for controlling multiple robotic components.
- **Design:** Houses an Arduino board, battery pack, and wire routing system, enabling control and customization of mechanisms.
- **Use Case:** Provides a centralized, portable power source for performances involving multiple moving elements.

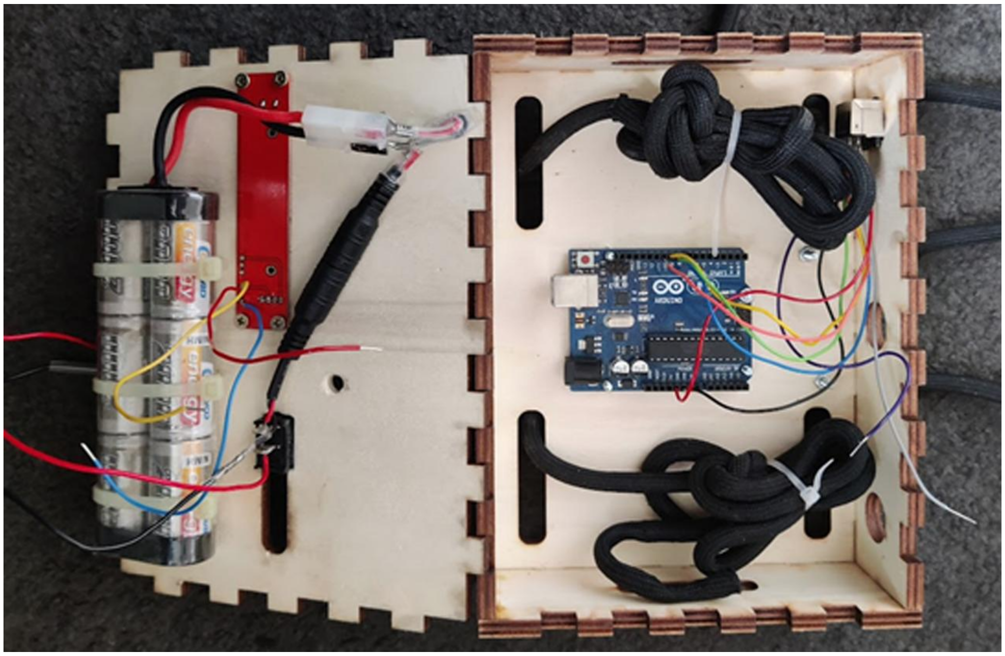

Figure 6.7: The Arduino backpack from laser-cut wood, with a battery, sliding potentiometer and cable port.

6.2 Developing the Website

This section covers the creation of the three toolkit versions, ensuring that users of varying expertise could engage with wearable robotics.

6.2.1 Website Structure and the Three Versions

To effectively support different user needs, the website was divided into three distinct versions:

1. **Artistic Toolkit:**
   - Focuses on visual inspiration and creative applications.
   - Features high-quality images and performance examples showcasing expressive robotic movements.

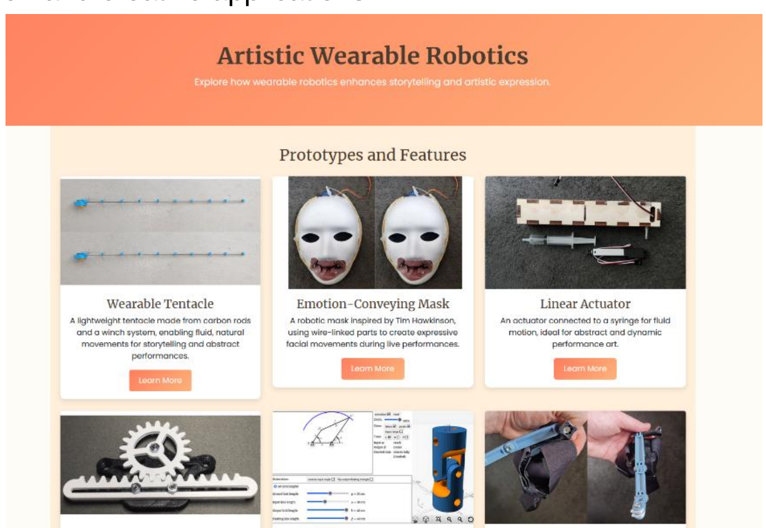

Figure 6.8: The artistic version of the website.

2. **Technological Toolkit:**
   - Provides technical documentation, CAD files, and coding instructions.
   - Includes step-by-step assembly guides for each mechanism.

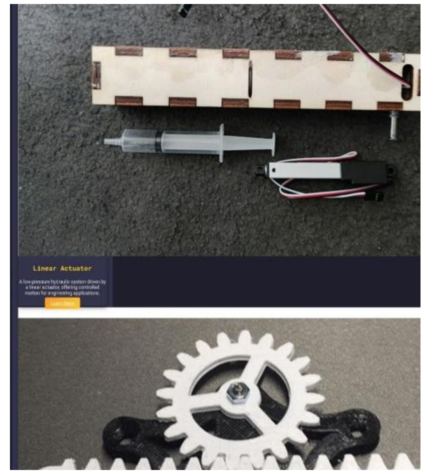

Figure 6.9: The technological version of the website loaded on smartphone.

3. **Educational Toolkit:**
   - Designed for beginners and educators who need clear, structured guidance.
   - Features interactive tutorials, a glossary of technical terms, and simplified assembly instructions.

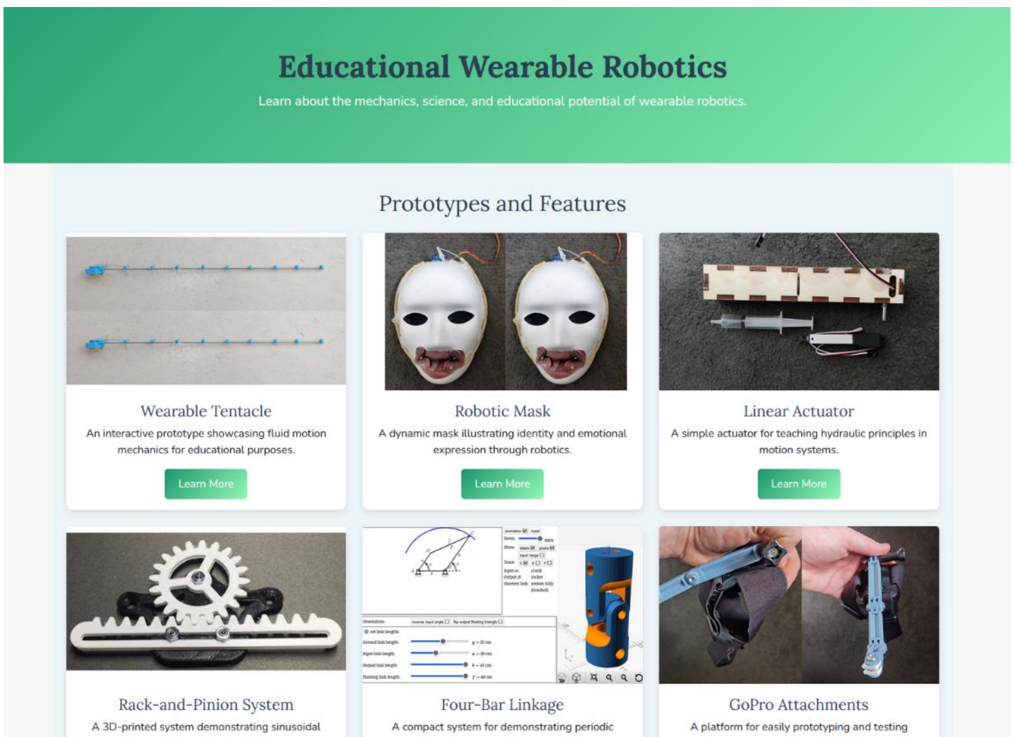

Figure 6.10: The educational version of the website.

6.2.2 Development Tools and Technologies

To build the website efficiently, a combination of web technologies and external tools was used:

- **HTML, CSS, and Bootstrap:** Provided the visual layout and responsive design.
- **JavaScript:** Enabled interactive elements like dropdown menus and real-time feedback forms.
- **GitHub Pages:** Hosted the site, ensuring version control and accessibility.
- **Adobe Photoshop:** Used to edit prototype images and ensure visual consistency.

- **ChatGPT Assistance:** Utilized for troubleshooting and generating code snippets to accelerate development.

All code written for this project and which bootstrap templates used are further elaborated in Appendix A.

6.2.3 Interactive Features and User Engagement

The website integrates various interactive components to enhance the learning experience:

- **Embedded Videos:** Demonstrate how the prototypes move in real-world applications.
- **Downloadable CAD Files:** Allow users to replicate and modify the designs.
- **Interactive Animations:** Highlight mechanical principles behind movement systems.

6.4 Validation of Functional Requirements

6.4.1 Functional Requirements Validation

The validation process confirmed that the core functional requirements of the toolkit were successfully met as can be seen in table 6.1. The educational website provides accessible resources for wearable robotics, ensuring compatibility across devices and browsers and maintaining open-source transparency for future adaptations. The user interface was designed to accommodate both technical and non-technical users, making navigation intuitive and the learning process accessible. Tutorials and explanations were developed in clear, jargon-free language, ensuring comprehensibility for a broad audience. Additionally, the website was hosted on a secure, reliable platform, ensuring stability and long-term usability.

However, some features remain unimplemented. The planned project submission and modification functionality was not completed, meaning users currently lack the ability to contribute their own projects directly. The search function to filter content based on interests and skill level was also not developed, limiting navigation efficiency. Similarly, content moderation tools and multilingual support were not integrated, reducing accessibility for a wider, global audience. While these omissions do not hinder the core usability of the toolkit, they represent valuable features for future iterations.

No.	Requirement	Status
1	The platform must be accessible online for users to engage with the toolkit.	Met
2	The interface must be user-friendly for both artists and technologists.	Met
3	The website must provide comprehensive guidance on both technical and artistic development.	Met
4	The platform must be open-source to ensure accessibility and community-driven contributions.	Met
5	The website should be hosted on a reliable platform with robust security measures.	Met
6	The website should ensure compatibility across different devices and browsers.	Met
7	Users should be able to submit projects and propose modifications, contributing to an iterative and evolving knowledge base.	Not Met
8	The content should be clear, jargon-free, and supplemented with explanations when necessary.	Met

9	The toolkit should allow for easy adaptation and customization, supporting a wide range of users.	Met
10	The platform could include search functionality to help users find relevant content by interest and skill level.	Not Met
11	A moderation system could ensure the quality and relevance of user-contributed content.	Not Met
12	The toolkit could support multilingual content, with English as the primary language.	Not Met
13	Additional language options could be implemented based on user demographics.	Not Met
14	The platform could include a Content Management System (CMS) for easy publishing and updates.	Not Met
15	User registration and profile creation could be included for saving progress and tracking engagement.	Not Met

Table 6.1: Functional requirements validation of toolkit/website.

6.4.3 Areas for Improvement

While the core functionalities of the toolkit and prototypes have been effectively implemented, there are still areas that require further development to fully realize the project's vision. The project submission and modification feature, intended to allow users to contribute their own wearable robotics designs, was not implemented, limiting collaborative engagement. Similarly, the search functionality, which was meant to allow users to filter content based on expertise level or artistic interest, was not included, making navigation less efficient for those with specific learning goals.

Another notable gap is the lack of a moderation system for user-generated content. Without such oversight, there is no mechanism to ensure the accuracy and relevance of community contributions. This absence reduces the potential for interactive knowledge-sharing and may require future integration of content validation tools or a peer-review system. Additionally, multilingual support was not introduced, restricting accessibility for non-English-speaking users. While the primary audience was English-speaking, future iterations could benefit from localization efforts to broaden the toolkit’s reach.

7. Evaluation

This chapter evaluates the effectiveness of the toolkit, prototypes, and website versions in addressing the main research question:
"How can a comprehensive toolkit be developed to guide artists in selecting and utilizing robotic movement systems to innovatively transform facial identity perception?"
The evaluation focuses on the website toolkit, as this is the primary medium through which users interact with the project. Rather than working directly with physical prototypes, users engage with the digital resources provided on the website, including tutorials, CAD files, and instructional materials. These resources enable artists and technologists to explore and integrate robotic movement systems into their artistic practice without requiring hands-on access to the physical prototypes.
This chapter encompasses the evaluation framework, system performance, user engagement, and synthesis of findings from user interviews. The results provide insights into how effectively the toolkit meets its objectives and highlight areas for improvement.

7.1 Evaluation Framework

The evaluation process was guided by the revised research questions and utilized both qualitative and quantitative methods. The goal was to assess how well the toolkit and its three versions—Artistic, Technological, and Educational—achieved the intended objectives of guiding artists and supporting innovation in wearable robotics.

7.1.1 Methods and Tools

The evaluation relied on two primary tools: questionnaires and semi-structured interviews. Participants, including artists, technologists, and educators, were provided with access to all three website versions and the physical prototypes. Feedback was collected using a structured questionnaire designed to address key evaluation criteria aligned with the research questions. This included:

1. **General Comparison Questions**: Participants rated each version on its overall appeal, clarity, navigation, and relevance to the main research question.
    - *Example*: "On a scale of 1 to 10, how visually and conceptually appealing did you find each version (Artistic, Technological, Educational)?"
2. **Version-Specific Questions**: Each version was assessed for its unique contributions:
    - Artistic Version: Focused on creative inspiration and showcasing artistic prototypes.
    - Technological Version: Assessed for technical depth and practical usability.
    - Educational Version: Evaluated for accessibility and learning support.
3. **Comparative Insights**: Participants were asked to identify their preferred version, discuss complementarities, and suggest improvements for enhancing the toolkit's overall value.

The complete questionnaire, informed consent form and information letter can be found in Appendix B, C and D respectively.

7.1.2 Participants and Stakeholders

The evaluation process involved two distinct participant groups, ensuring a balanced assessment of the toolkit's effectiveness from both domain-relevant and external perspectives.
The first group consisted of three students (A1–A3) from the fields of Creative Technology and Interaction Technology, who possess knowledge directly related to the project's objectives. Their feedback provided valuable insights into the technical depth, usability, and artistic applications of the toolkit. Given their background, they were able to assess the toolkit's potential in guiding users through the integration of robotic movement systems into performance art.
The second group included six experts (B1–B6) from diverse professional fields, such as computer science, education, and engineering. While these experts may not have direct experience with wearable robotics or performance art, their feedback was crucial in evaluating the clarity, accessibility, and interdisciplinary applicability of the toolkit. Their perspectives ensured that the website was assessed not only for its technical accuracy but also for its ability to be understood and utilized by a broader audience beyond its immediate field.
This mixed-method approach enabled an evaluation across multiple dimensions, from the technical functionality of the prototypes to the educational value and user experience of the website. While the students (A1–A3) provided expert insight into how well the toolkit aligns with its intended use case, the broader experts (B1–B6) evaluated whether the toolkit is intuitive and applicable for users unfamiliar with wearable robotics.
By involving both directly relevant and adjacent stakeholder groups, the evaluation ensures that the toolkit is comprehensive, accessible, and effective for a diverse range of users, from artists seeking inspiration to technologists and educators integrating wearable robotics into creative applications

7.1.3 Evaluation Criteria

The evaluation criteria were designed to systematically assess the effectiveness of the toolkit and its three website versions in guiding artists toward utilizing robotic movement systems for artistic expression. These criteria were developed in alignment with the questionnaire structure used in the study, ensuring a comprehensive assessment of usability, content quality, and engagement.
The following aspects were evaluated based on user responses:

- **Content Quality:** Evaluated through questions on clarity, comprehensiveness, and relevance of tutorials, case studies, and available resources. Participants rated how well the provided content supported their understanding of wearable robotics (as captured in Questions 3, 4, 5, and 9 of the questionnaire).
- **Usability:** Measured by how easily participants could navigate the website, interact with its features, and access relevant information. This aligns with Question 2 on navigation clarity and ease of use.
- **Effectiveness:** The ability of the toolkit to successfully guide users in applying robotic movement systems for artistic expression. This was assessed through user responses regarding how well the versions aligned with the main research question (Question 3) and the specific evaluation of the Educational version's support for learning and experimentation (Question 9).

- **Inspiration and Creativity:** The toolkit's impact on fostering new artistic ideas and its ability to engage users in creative experimentation. This was measured through responses regarding the Artistic version's ability to inspire new projects (Question 4).
- **Technical Accuracy:** The depth and correctness of the information presented in the Technological version. This was primarily assessed through Questions 6 and 7, where users evaluated the technical depth and practical usability of the provided information.
- **Engagement and Community Building:** The toolkit's ability to facilitate collaboration, discussion, and user interaction. While this was an intended feature of the toolkit, the current version included placeholders for these functionalities. Participants provided insights on how the toolkit could better support engagement in Questions 10 and 11.

7.1.4 Data Collection and Analysis

Participants provided ratings on a scale of 1 to 10 for key questions, with open-ended responses gathered for qualitative insights. Data analysis involved the aggregating and comparing of ratings across the three website versions. It involved the thematic analysis of qualitative responses to identify recurring strengths and areas for improvement. And lastly the cross-referencing of findings with the research questions to ensure alignment and identify gaps.
By employing this structured framework, the evaluation process aimed to provide a comprehensive understanding of how effectively the toolkit supports its intended audience and fulfils its research objectives.

7.2 Synthesis of User Evaluation

Category \ Interviewee	A1	A2	A3	*Avg. Gr. A*	B1	B2	B3	B4	B5	B6	*Avg. Gr. B*
Overall Appeal (1-10)	9	8	8	*8.33*	7	8	7	8	8	7	*7.50*
Clarity & Navigation (1-10)	8	8	7	*7.67*	8	9	7	8	8	8	*8.00*
Relevance to Toolkit Goals (1-10)	9	8	9	*8.67*	8	7	7	9	8	7	*7.67*
Artistic Version Inspiration (1-10)	9	8	8	*8.33*	7	7	8	7	9	7	*7.50*
Artistic Prototypes Showcase (1-10)	8	9	8	*8.33*	7	7	7	8	8	6	*7.17*
Technical Depth (1-10)	8	7	9	*8.00*	6	9	7	9	8	6	*7.50*
Practical Usability (1-10)	8	7	8	*7.67*	7	9	8	9	8	7	*8.00*
Accessibility for Beginners (1-10)	7	8	7	*7.33*	9	7	8	7	7	9	*7.83*
Learning Support (1-10)	8	8	9	*8.33*	8	7	8	8	8	8	*7.83*
Preferred Version	Tec	Art	Tec	-	Edu	Tec	Art	Tec	Art	Edu	-
Combined Effectiveness (1-10)	8	9	8	*8.33*	8	9	8	9	8	9	*8.17*

Table 7.1: Synthesis of User Evaluation.

The evaluation process underscored the strengths and areas for improvement across the toolkit's three versions, as can be seen in table 7.1. Participants praised the Artistic version for its ability to inspire creativity and connect with cultural contexts, making it a standout choice for those seeking artistic innovation. Meanwhile, the Technological version was commended for its robust foundation in explaining movement systems and offering practical implementation guidance, appealing to users with a technical focus. The Educational version excelled in bridging the gap for beginners, providing accessible content and clear guidance that resonated with less technically inclined users.

A recurring insight was the importance of better integration between the versions. Participants frequently highlighted the value of a unified toolkit that facilitates seamless transitions between creative inspiration, technical depth, and accessible learning. Suggestions for achieving this included embedding cross-links between sections and creating pathways tailored to different user levels. Such enhancements would ensure that the toolkit caters effectively to a diverse audience, from novices to advanced users.

Another key theme was the significance of interactivity and community engagement. Many participants expressed a strong interest in features such as user forums, project-sharing capabilities, and collaborative tools that could foster a sense of community. These additions would not only enhance user satisfaction but also expand the toolkit's reach by encouraging knowledge exchange and collaboration among users.

The evaluation also revealed areas for improvement in navigation and the presentation of examples. While the overall layout and design were appreciated, some participants suggested streamlining the navigation system and adding more case studies or detailed examples to enrich user engagement. This feedback points to opportunities for refining the toolkit to better meet user expectations and needs.

7.3 Validation of Non-Functional Requirements

The non-functional requirements were largely met, as detailed in table 7.2, ensuring the platform’s efficiency, usability, and scalability. The website was designed to be intuitive, supporting both artists and technologists regardless of their prior expertise. Structured tutorials, clear explanations, and a predictable navigation structure allowed users to engage with the content effectively. Additionally, the website met performance expectations, loading efficiently across different devices and maintaining compatibility with major browsers.

However, a notable limitation was the absence of content moderation mechanisms for user-generated contributions. While the platform was structured to allow community-driven input, no active filtering or verification system was implemented. Future iterations should consider integrating moderation tools to ensure quality control. Furthermore, while the website met initial performance benchmarks, ongoing optimization will be necessary to sustain responsiveness as more content and interactive features are introduced.

No.	Non-Functional Requirement	Status
1	The interface must be intuitive and user-friendly, ensuring ease of use for diverse user groups.	Met
2	The platform must present information in a structured and accessible manner, supporting users of all skill levels.	Met
3	All content must be clear, understandable, and jargon-free, with explanations where necessary.	Met
4	The website must implement secure hosting with HTTPS encryption to protect user data and ensure high availability.	Met
5	The website should have a simple and predictable navigation structure to improve accessibility.	Met
6	Users should perceive content as high quality and relevant, ensuring a positive user experience.	Met
7	The website should load within three seconds on standard internet connections for optimal performance.	Met
8	The platform should maintain compatibility with all major browsers and devices, ensuring accessibility across technologies.	Met

Table 7.2: Validation of Non-Functional Requirements.

7.4 Insights into User Engagement and Satisfaction

Across all three versions of the toolkit, the feedback indicated positive reception, but distinct preferences emerged based on users' backgrounds.

- The Artistic Version was highly praised for its ability to inspire creativity. Participants, particularly those with artistic inclinations, appreciated how prototypes like the wearable tentacle and robotic mask encouraged storytelling and experimental performance. However, some suggested that additional real-world applications could make the toolkit more relatable to broader audiences.
- The Technological Version received strong support from users with technical expertise. It was valued for its depth, providing comprehensive explanations of movement systems and the mechanics behind wearable robotics. However, its complexity posed a challenge for those with limited technical knowledge, leading to suggestions for simplified pathways and introductory tutorials to assist beginners.
- The Educational Version stood out for its accessibility, offering structured tutorials and jargon-free explanations. This version was particularly well received by non-technical users, who found it helpful in breaking down complex concepts. However, several participants noted the lack of resources tailored to intermediate users, suggesting a need for more advanced tutorials to bridge the gap between beginner and expert levels.

Participants also highlighted the complementary nature of the three versions, noting that while each served distinct purposes, a more seamless transition between them would improve the learning experience. Some users suggested embedding cross-references, hyperlinks, or navigation cues to encourage exploration across different sections.

Overall, the evaluation confirmed that the core usability and functionality of the toolkit were successful, meeting both the technical requirements and the needs of diverse users. However, improvements such as content moderation, better integration between toolkit versions, and additional intermediate-level resources were identified as key areas for future development.

7.5 Conclusion and Key Insights

The evaluation process demonstrated that the Wearable Robotics Toolkit successfully serves as a resource for artists and technologists, with each version addressing distinct user needs. The Artistic Version was praised for its ability to inspire creativity, the Technological Version was valued for its in-depth technical insights, and the Educational Version effectively provided accessible content for beginners. However, key areas for improvement were also identified, including better integration between versions, enhanced interactivity, and clearer navigation.

A recurring theme was the need for seamless transitions between the three versions, ensuring that users can fluidly move from creative inspiration to technical depth and structured learning. Participants suggested embedding cross-references and guided pathways to create a more unified and user-friendly experience. Additionally, community engagement features, such as forums and project-sharing functionalities, were highlighted as potential enhancements that could foster knowledge exchange and collaboration among users.

While the website met all non-functional requirements, as confirmed in table 7.2, the absence of moderation tools for user-generated content remains an area for future improvement. This gap suggests the need for a content verification mechanism to ensure that community contributions remain relevant and of high quality may the functionality be added in the future. Similarly, ongoing performance optimizations will be necessary as the toolkit expands with additional resources.

Overall, the evaluation confirms that the Wearable Robotics Toolkit is a valuable platform for bridging the gap between art and technology. By addressing the identified areas for enhancement, the toolkit has the potential to become a more robust and engaging resource that empowers users to explore, innovate, and integrate robotic movement systems into artistic expression.

8. Discussion & Future Work

This chapter provides an in-depth analysis of the outcomes of this project, evaluates its challenges, and discusses the societal and ethical implications of wearable robotics in artistic contexts. It also identifies potential future directions to enhance the toolkit and broaden its applications. By reflecting on the key findings and integrating insights from earlier chapters, this section offers a roadmap for the continued evolution of wearable robotics in art and technology.

8.1 Key Findings and Interpretations

The development and evaluation of the toolkit revealed several significant insights into its effectiveness and impact. Each version of the toolkit served distinct purposes, catering to diverse user needs. The Artistic version excelled in fostering creativity and connecting wearable robotics to cultural and artistic contexts. By showcasing prototypes like the robotic mask and wearable tentacle, the Artistic version demonstrated how movement systems could enhance storytelling and self-expression. The robotic mask enabled performers to dynamically shift facial expressions in real time, allowing for fluid emotional transitions that traditional masks lack. The wearable tentacle, with its organic, flowing motion, expanded bodily expression beyond human limits, introducing abstract and non-verbal storytelling elements.

The Technological version provided a robust foundation for users interested in understanding and implementing the mechanical and programming aspects of wearable robotics. Detailed explanations and in-depth resources offered a pathway for users to explore technical solutions, which was highly appreciated by participants with a technical background. However, the complexity of this version posed challenges for less experienced users, emphasizing the need for tiered guidance to accommodate varying levels of expertise.

The Educational version bridged the gap for beginners by offering clear, structured tutorials and accessible explanations. It demystified complex concepts and empowered users with limited technical or artistic experience to engage with wearable robotics. Participants valued its straightforward approach, although they highlighted the need for additional intermediate resources to support users as they advanced.

One of the overarching themes was the complementary nature of the three versions. Participants frequently noted the potential for greater integration, suggesting pathways that seamlessly transition users between creative inspiration, technical depth, and accessible learning. Such a unified approach would enable users to explore wearable robotics holistically, catering to both novice and advanced practitioners.

8.2 Challenges and Limitations

The project faced several challenges, particularly in balancing the needs of diverse user groups. The Technological version’s depth, while a strength for advanced users, created barriers for beginners. Simplifying certain sections and offering tiered content could help address this limitation. Similarly, while the Educational version successfully made wearable robotics accessible, it lacked resources for intermediate users, limiting its ability to guide users through a gradual learning progression.

Another significant challenge was the lack of integration between the three versions. Despite their individual strengths, the absence of cross-references and tailored pathways reduced the toolkit's cohesiveness. Participants noted that they often had to navigate between versions manually, which disrupted the learning experience. Improving navigation, streamlining website structure, and adding real-world case studies were frequently suggested to enhance relatability and engagement.

A key limitation of the evaluation was the absence of physical prototype testing in the user studies. While the website provided CAD files, tutorials, and theoretical guidance, participants did not engage with the actual robotic mechanisms, meaning that usability in hands-on artistic settings was not assessed. Future research should incorporate direct prototype interaction to evaluate how artists physically work with wearable robotics beyond digital exploration.

Finally, resource and time constraints impacted the development of the website itself. The limited availability of time to code the website restricted the implementation of advanced features, such as interactive design tools and dynamic content customization. Additionally, hosting limitations affected the scalability of the platform, preventing the integration of more complex functionalities, such as user project submissions or live prototype simulations. Expanding the team with more web development expertise and securing a more robust hosting solution would enable the toolkit to support richer interactive experiences and a growing user base in future versions.

8.3 Future Directions in Wearable Robotics

The findings from this project highlight several promising directions for the advancement of wearable robotics, both in terms of toolkit development and broader industry and academic engagement.

One key area for improvement is the integration of the three toolkit versions into a unified platform. Currently, users must navigate between separate Artistic, Technological, and Educational versions, limiting accessibility and continuity. Embedding cross-links, adaptive pathways, and dynamic user guidance would streamline the experience, allowing users to transition seamlessly between creative inspiration, technical exploration, and structured learning.

Interactivity and community engagement emerged as critical opportunities for growth. The addition of user forums, collaborative tools, and project-sharing platforms could foster a dynamic environment where artists and technologists exchange ideas, share experiences, and refine wearable robotics projects collaboratively. Hosting live workshops, virtual events, and knowledge-sharing sessions would further encourage interdisciplinary engagement and facilitate hands-on learning in a remote setting.

Beyond the toolkit itself, industry and academia should prioritize:

- **Unified and Adaptive Platforms:** Stakeholders should develop multi-functional resources that seamlessly integrate artistic, technological, and educational aspects. This approach would cater to diverse user groups, supporting both beginners and experienced practitioners.
- **Enhanced Interactivity:** Developers and researchers should prioritize interactive and participatory features in wearable robotics platforms. Implementing interactive prototypes,

real-time simulations, and modular customization tools can improve user engagement and practical application.

- **Focus on Accessibility:** Ensuring clear, jargon-free content and intuitive interface design lowers the barrier to entry for users with limited technical experience. Open-source accessibility also plays a crucial role in democratizing wearable robotics education and fostering inclusive participation.
- **Sustainable Practices:** The use of eco-friendly materials, energy-efficient actuation systems, and modular designs should be explored to reduce the ecological footprint of wearable robotics. Industry and academic researchers should collaborate to develop low-impact fabrication methods that balance innovation with environmental responsibility.
- **Ethical Frameworks:** Institutions must establish ethical guidelines for wearable robotics, addressing issues of cultural sensitivity, user safety, and privacy. Frameworks that consider the societal and artistic implications of robotic augmentation will help ensure responsible development and application.

Expanding the content within the toolkit is another critical future step. Additional case studies, intermediate tutorials, and advanced prototypes could help bridge gaps identified during the evaluation. Exploring emerging movement systems, such as AI-driven actuation, biomimicry-based designs, or soft robotics, would broaden the creative and technical possibilities in wearable robotics. Additionally, fostering partnerships with cultural experts and interdisciplinary teams would ensure that future projects remain both culturally sensitive and artistically innovative.

8.4 Societal and Ethical Implications

The project underscores the transformative potential of wearable robotics while highlighting the importance of ethical and societal considerations. Cultural sensitivity is paramount, particularly when drawing inspiration from traditional practices. The toolkit’s inclusion of guidelines for ethical design and cultural respect reflects its commitment to responsible innovation. Future iterations should continue to prioritize inclusivity, ensuring that designs are not only respectful but also accessible to diverse audiences.

User safety is another critical consideration. By employing low-power electronics and prioritizing safety in prototype designs, the project adhered to ethical standards. Future work should explore advanced safety features, especially as wearable robotics become more complex and interactive.

Sustainability is a growing concern in the field of robotics. The project’s emphasis on open-source resources and accessible materials aligns with sustainable practices, but future iterations should further explore environmentally friendly materials and energy-efficient designs. These efforts would reduce the ecological footprint of wearable robotics and contribute to global sustainability goals.

Finally, the toolkit’s commitment to accessibility ensures that wearable robotics remain a democratized field. By offering clear, jargon-free content and open-source resources, the project lowers barriers to entry for artists with limited technical expertise. This approach not only empowers individual creators but also fosters a broader appreciation for the intersection of art and technology.

9. Conclusion

This chapter encapsulates the journey of developing the wearable robotics toolkit, evaluating its contributions, challenges, and implications for the intersection of art and technology. Through an interdisciplinary approach, the project aimed to create a comprehensive resource that empowers artists, technologists, and educators to integrate robotic movement systems into performance art. The findings from this research provide valuable insights into how wearable robotics can transform artistic expression while highlighting areas for further refinement.

9.1 Summary of Contributions and Achievements

The central research question guiding this project was:
"How can a comprehensive toolkit be developed to guide artists in selecting and utilizing robotic movement systems to innovatively transform facial identity perception?"
The project successfully addressed this question by developing an open-access toolkit divided into Artistic, Technological, and Educational versions, each tailored to distinct user needs. The Artistic version focused on inspiring creativity by showcasing prototypes like the robotic mask and wearable tentacle, demonstrating how movement can shape identity, storytelling, and performance. The Technological version provided in-depth resources on the mechanics and programming of wearable robotics, equipping users with the technical skills to customize and implement movement systems. Meanwhile, the Educational version offered structured, jargon-free tutorials that made wearable robotics accessible to beginners, ensuring that users of all experience levels could engage with the material.
Beyond its structural contributions, the project followed the Creative Technology Design Process, employing iterative prototyping, stakeholder engagement, and usability testing to refine the toolkit. The evaluation process demonstrated that the toolkit effectively supported users in exploring and applying robotic movement systems, while also identifying areas for future development, particularly in cross-version integration and interactivity.

9.2 Reflections on Wearable Robotics and Identity

One of the most significant findings of this research was the potential of robotic movement to reshape identity perception in performance art. The robotic mask and wearable tentacle prototypes exemplified how movement-based augmentations can enhance self-expression, emotional storytelling, and audience engagement. The dynamic nature of these systems enables fluid representations of identity, challenging static or conventional modes of presentation.
However, as wearable robotics advance, ethical considerations surrounding cultural sensitivity, sustainability, and inclusivity must remain at the forefront. The toolkit provided initial steps toward responsible development by incorporating open-source principles and advocating for accessible and sustainable materials, but further refinement is needed to ensure that wearable robotics respect cultural contexts and are adoptable across diverse artistic communities.

9.3 Final Thoughts and Vision for the Future

The wearable robotics toolkit marks an important step in bridging creativity and technology, offering a resource that empowers artists to explore robotic movement in new ways. The project has demonstrated that movement systems can be successfully adapted into wearable, expressive forms, but also highlighted key areas for continued improvement, such as greater integration between the three toolkit versions, enhanced interactivity, and more structured pathways for user progression.

Looking ahead, industry and academia can play a crucial role in advancing wearable robotics by fostering collaborations between artists, engineers, and cultural researchers. Future toolkit developments should incorporate AI-driven movement systems, biomimetic designs, and expanded interdisciplinary engagement to further push the boundaries of wearable robotics. Ethical and sustainable practices must continue to be a guiding principle, ensuring that the evolution of wearable robotics benefits both artistic innovation and social responsibility.

In conclusion, this research has successfully demonstrated how a comprehensive toolkit can guide artists in selecting and utilizing robotic movement systems to transform facial identity perception in performance art. By building upon the project's successes and addressing its limitations, the toolkit has the potential to become a cornerstone in the field of wearable robotics, fostering innovation at the intersection of art, technology, and identity.

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Appendix A – Website Code & Bootstrap Template

The educational website supporting the Wearable Robotics Toolkit was built using HTML, CSS, Bootstrap, and JavaScript. Bootstrap was chosen as the primary front-end framework due to its responsive design capabilities, ease of use, and extensive component library. This appendix outlines the Bootstrap templates used, highlights key modifications, and provides examples of code customizations. The full source code is available at**:**
GitHub Repository: https://github.com/MatthijsKleine/WearableRobotics

A.1 Bootstrap Templates Used

The website design was based on modified **Bootstrap templates**, which provided a structured foundation for a responsive and user-friendly interface. The following components were utilized:

- **Navbar:** Based on Bootstrap's `navbar-light` with dropdowns for navigation.
- **Hero Sections:** Modified `jumbotron` and `container-fluid` layouts to introduce each toolkit version.
- **Cards & Grids:** Used `card` components to present prototypes in an organized format.
- **Modals & Buttons:** Integrated `modal` pop-ups for detailed explanations of prototypes.
- **Forms & Interactive Elements:** Incorporated Bootstrap's `form-control` elements for potential user input.

A.2 Key Customizations

While Bootstrap provided a strong foundation, several custom modifications were required to tailor the website for the Wearable Robotics Toolkit.

A.2.1 Custom Navigation Bar

The standard Bootstrap navigation was modified to improve the user experience and maintain consistency across the Artistic, Technological, and Educational versions of the website.
Original Bootstrap Code:

```
<nav class="navbar navbar-expand-lg navbar-light bg-light">
  <a class="navbar-brand" href="#">Wearable Robotics</a>
  <button class="navbar-toggler" type="button" data-toggle="collapse" data-
target="#navbarNav">
    <span class="navbar-toggler-icon"></span>
  </button>
  <div class="collapse navbar-collapse" id="navbarNav">
    <ul class="navbar-nav">
      <li class="nav-item"><a class="nav-link" href="#">Home</a></li>
      <li class="nav-item"><a class="nav-link" href="#">About</a></li>
    </ul>
  </div>
</nav>
```

Modified Code:

```
<nav class="navbar navbar-expand-lg navbar-dark bg-primary">
  <a class="navbar-brand" href="#">Wearable Robotics Toolkit</a>
  <button class="navbar-toggler" type="button" data-toggle="collapse" data-
target="#navbarNav">
    <span class="navbar-toggler-icon"></span>
  </button>
  <div class="collapse navbar-collapse" id="navbarNav">
    <ul class="navbar-nav mx-auto">
      <li class="nav-item"><a class="nav-link"
href="artistic.html">Artistic</a></li>
      <li class="nav-item"><a class="nav-link"
href="technological.html">Technological</a></li>
      <li class="nav-item"><a class="nav-link"
href="educational.html">Educational</a></li>
    </ul>
  </div>
</nav>
```

Changes:

- Color scheme adjusted (`navbar-dark bg-primary`) for better readability.
- Navigation links centralized (`mx-auto`) to improve aesthetics.
- Sections linked directly to corresponding toolkit pages.

A.2.2 Hero Section Modifications

Bootstrap's Jumbotron was initially used for the hero sections but was replaced with a more flexible `container-fluid` approach for better responsiveness.

Original Bootstrap Code:

```
<div class="jumbotron">
  <h1 class="display-4">Welcome!</h1>
  <p class="lead">Explore the world of wearable robotics.</p>
</div>
```

Modified Code:

```
<div class="container-fluid hero-section text-center">
  <h1>Wearable Robotics Toolkit</h1>
  <p class="lead">Empowering artists and technologists through movement
systems.</p>
```

Changes:

- Replaced **`jumbotron`** with `container-fluid` for full-width responsiveness.
- Applied custom CSS for typography adjustments matching the toolkit's branding.

A.2.3 Card Components for Prototypes

Bootstrap’s card components were used to showcase each prototype across the three toolkit versions.

Original Bootstrap Code:

```
<div class="card" style="width: 18rem;">
  <img src="tentacle.jpg" class="card-img-top" alt="Tentacle">
  <div class="card-body">
    <h5 class="card-title">Tentacle</h5>
    <p class="card-text">A wearable tentacle mechanism for expressive
storytelling.</p>
  </div>
</div>
```

Modified Code:

```
<div class="col-md-4">
  <div class="card feature-card">
    <img src="images/tentacle.png" class="card-img-top" alt="Wearable
Tentacle">
    <div class="card-body">
      <h3>Wearable Tentacle</h3>
      <p>A modular tentacle built with carbon rods and a winch system.</p>
      <a href="tentacle.html" class="btn btn-primary">Learn More</a>
    </div>
  </div>
</div>
</div>
```

Changes:

- Integrated grid layout (`col-md-4`) for a more structured layout.
- Added "Learn More" button linking to detailed prototype pages.

A.3 Hosting and Deployment

The website was deployed using GitHub Pages, ensuring an easily accessible and scalable platform. The repository includes all HTML, CSS, and JavaScript files, allowing for future iterations and contributions.

Appendix B – Interview Questionnaire

Name: **Date:**

General Comparison Questions

1. **Overall Appeal**: On a scale of 1 to 10, how visually and conceptually appealing did you find each version (Artistic, Technological, Educational)?
   - What specific aspects contributed to your rating (e.g., layout, colors, interactivity)?

2. **Clarity and Navigation**: Rate how easy it was to understand and navigate each version (1 being confusing and 10 being completely intuitive).
   - Were there any sections or features that stood out positively or negatively?

3. **Relevance to the Research Question**: How well did each version align with the toolkit's goal of guiding artists in using robotic movement systems (1 = Not relevant, 10 = Highly relevant)?
   - Which version do you believe best addressed this goal, and why?

Artistic Version

4. **Artistic Inspiration**: Rate how well the Artistic version inspired creative ideas for wearable robotics projects (1 = Not inspiring, 10 = Extremely inspiring).
   - Did the design or content feel tailored to artists focusing on creativity?

5. **Prototypes Showcase**: Rate how effectively the Artistic version showcased prototypes like the tentacle and mask for artistic applications (1 = Poorly, 10 = Perfectly).
   - What improvements could make the content more impactful for artistic users?

Technological Version

6. **Technical Depth**: Rate the level of technical depth provided in the Technological version (1 = Insufficient, 10 = Comprehensive).
   - Did it provide enough information on the mechanisms and programming involved in the prototypes?

7. **Practical Usability**: Rate how well the Technological version supported practical applications of the prototypes (1 = Not useful, 10 = Highly practical).
   - What additional technical details or resources would have been helpful?

Educational Version

8. **Accessibility for Beginners**: Rate how accessible the Educational version was for users with limited technical or artistic experience (1 = Not accessible, 10 = Extremely accessible).
   - Were the tutorials and resources presented in a way that was easy to understand?

9. **Learning Support**: Rate how well the Educational version supported learning and experimentation (1 = Poorly, 10 = Exceptionally well).

  - Did the guides and case studies provide enough context to support independent exploration?

Comparative Insights

10. **Preferred Version**: If you were to recommend one version to a new user, which would it be and why?

11. **Complementarity**: Do you feel that the three versions complement each other well? Rate their combined effectiveness on a scale of 1 to 10.

  - How could the versions work better together to enhance the toolkit's overall value

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Open Feedback

12. **Overall Impression**: What did you find most valuable about the toolkit?

13. **Suggestions for Improvement**: Are there any features or resources you think the toolkit should include to better serve its goals?

14. **General Feedback**: Do you have any other comments or suggestions about the toolkit, website, or prototypes?

Appendix C – Informed Consent Form

Consent Form for Wearable Robotics and Facial Identity Perception

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

If also taking part in the simultaneous evaluation by Nathan van Daal please ensure consent is given to both evaluations explicitly.

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated 27/09/2024 or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
I understand that taking part in the study involves participating in a series of activities designed to explore the integration of wearable robotics in artistic expressions, including filling out questionnaires, engaging in interviews, and interacting with wearable robotic devices. The information will be captured through audio-recorded interviews, video-recorded interactions with the devices, and surveys completed by the researcher. All audio and video recordings will be transcribed as text, and the original recordings will be securely destroyed after transcription.	○	○
OPTIONAL (delete if not needed):		
Risks associated with participating in the study		
I understand that taking part in the study involves the following risks: minimal physical discomfort from wearing the devices, potential mental fatigue from participation duration, and a slight risk of personal identity exposure through the dissemination of anonymized results.	○	○
Use of the information in the study		
I understand that information I provide will be used for the development of academic knowledge in the field of wearable robotics and artistic expression, contributing to reports, publications, and potentially a website dedicated to the project. Personal information that can identify me, such as my name or where I live, will not be shared beyond the study team. I agree that anonymized information I provide can be quoted in research outputs but do not consent to the use of my real name for quotes.	○	○
I understand that personal information collected about me that can identify me, such as my name, will not be shared beyond the study team.	○	○
I agree that anonymized information I provide can be quoted in research outputs but do not consent to the use of my real name for quotes.	○	○
Alternatively, I consent to and prefer the use of my real name alongside my quotes.	○	○

Consent to be Audio/video Recorded

I agree to be audio/video recorded. ○ ○

Future use and reuse of the information by others

I give permission for the anonymized transcripts and survey data that I provide to be archived in as an appendix to this thesis in the University of Twente Theses Repository so it can be used for future research and learning. The data will be fully anonymized to ensure my identity is protected, and access restrictions will be applied to exclude commercial use and ensure safeguarded access. ○ ○

I agree that my anonymized information may be shared with other researchers for future research studies similar to this study. The information shared will not include any data that can directly identify me, and researchers will not contact me for additional permission to use this information. ○ ○

Signatures

_______________________________ _____________________ ________

Name of participant
(and legal representative If applicable) Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Matthijs Kleine________ __________________ ________

Researcher name Signature Date

Study contact details for further information:

Matthijs Kleine
Creative Technology Student University
of Twente, EEMCS
m.j.kleine@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science: ethicscommittee-CIS@utwente.nl

Appendix D – Information Letter

Subject: Participant Information Letter for Wearable Robotics and Facial Identity Perception Dear Participant,

Thank you for considering participation in our research study titled "Wearable Robotics and Facial Identity Perception." This study is conducted by Matthijs Kleine, student, at University of Twente. Below you will find detailed information about the research, what your participation would involve, and your rights as a participant. *The evaluation for this research will be done simultaneously with the evaluation for the research of Nathan van Daal, in case of participation in both studies please ensure consent is given for both evaluations.*

Purpose of the Research: The primary aim of this research is to explore and identify movement systems in robotics that can be innovatively designed to transform facial identity perception artistically. This involves understanding the potential of various robotic movement systems to influence and alter perceptions of facial identity in an artistic manner.

Session Details: Your participation will involve engaging with wearable robotic masks and providing feedback on their usability, comfort, and the innovativeness of the mechanisms. Participation will also involve looking at the artistic toolkit website that was developed for this research. The session is expected to last approximately 1 hour, during which you will be asked to interact with different prototypes and share your experiences and perceptions.

Benefits and Risks: Participating in this study offers no direct benefits to you. However, your contribution will be instrumental in advancing the understanding of wearable robotics in artistic contexts. The potential risks associated with participating are minimal and primarily involve the time commitment required for the session. This research project has been reviewed and approved by the Ethics Committee Information and Computer Science at the University of Twente.

Withdrawal Procedures: You have the right to withdraw from the study at any point without any penalty or loss of benefits to which you are otherwise entitled.

Data Collection and Privacy: We will collect personal data necessary for the research, such as feedback on the prototypes. Strict confidentiality protocols are upheld to safeguard your personal information. Data will be de-identified, and access will be controlled and limited to the research team.

Usage and Safeguarding of Data: The collected data will be used for research purposes only. It will be stored securely and only accessible to the research team. Findings may be disseminated through academic publications or presentations, where your anonymity will be preserved.

Data Retention: The research data will be retained for a period of maximum 3 months, after which it will be securely disposed of.

Contact Information: For questions about the research, please contact Matthijs Kleine at m.j.kleine@student.utwente.nl. For complaints, contact the Ethics Committee Information and Computer Science at ethicscommittee-cis@utwente.nl.

By agreeing to participate, you acknowledge that you have read and understood the information provided above. We appreciate your time and contribution to this important research. Sincerely,

Matthijs Kleine
Creative Technology Student University of
Twente, EEMCS m.j.kleine@student.utwente.nl

Appendix E – Generative AI Policy Extension

*"During the preparation of this work the author used **ChatGPT** in order to **increase readability and text cohesion.** After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work."*

Student Name: Matthijs Kleine   Assignment: Bachelor Thesis

I hereby state that I have recorded all entries utilizing generative AI technologies such as ChatGPT to develop my written assignment.

Electronic Signature: *Date: 23/02/2025*

Prompt or original text inserted	***Output***	***Footnote***
Please combine the separately written parts into cohesive paragraphs, fix the grammar and spelling and give suggestions for improvements for the following text: [Insert manually typed report]	The current version of the report	I basically first wrote the entire report without caring about grammar, spelling or cohesion. Then I entered it into ChatGPT, read through the results, changed what I thought needed to be changed, and that's my current result.*

* I can provide the full prompt through mail if required but it adds a very large amount of words to the already large document and makes it unreadable.