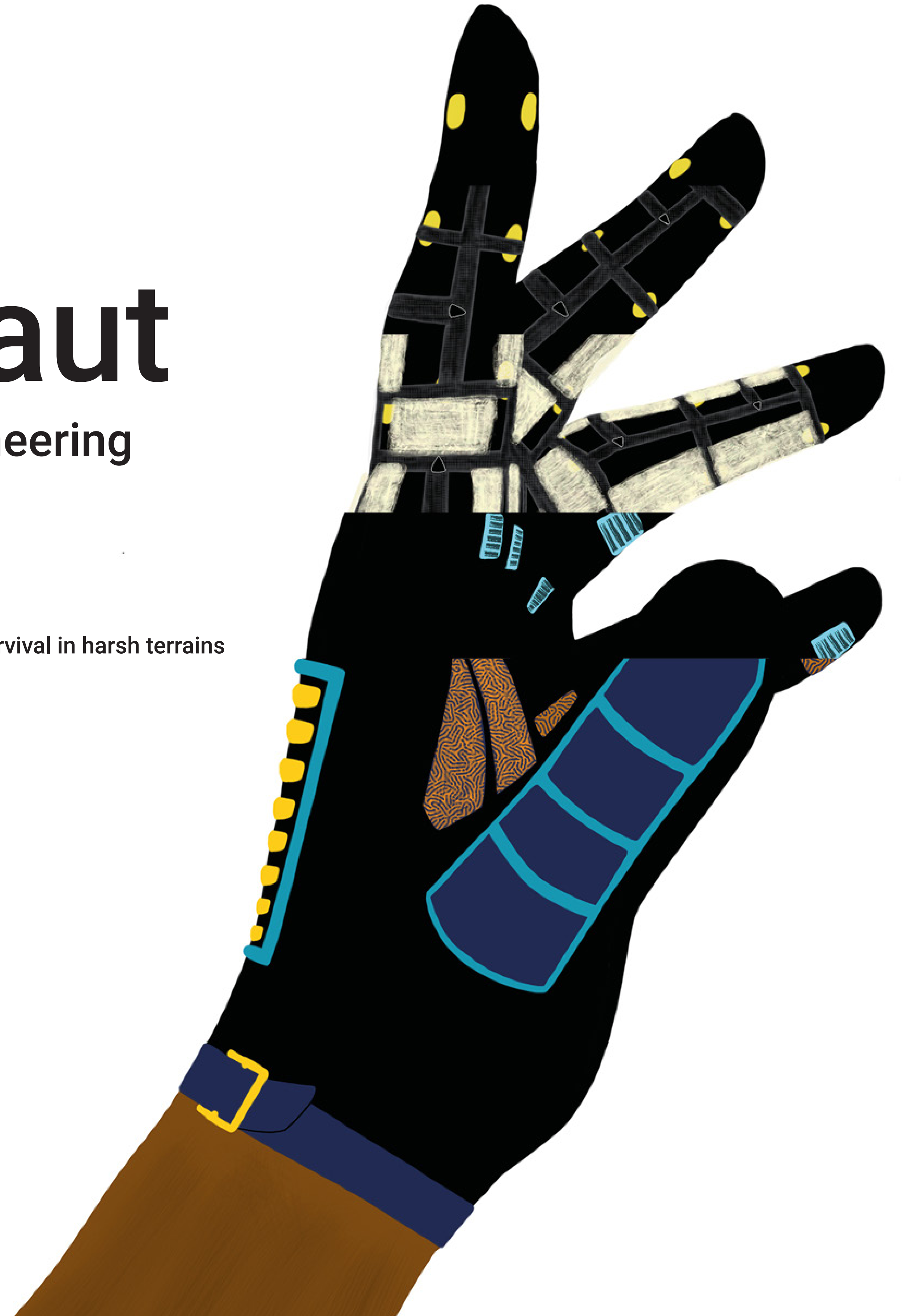
THE GLASGOW SCHOOL OF ART

Juggernaut

MSc Product Design Engineering
Tanuj Piplani

An active device that enhances human capabilities for survival in harsh terrains



University of Glasgow

Executive Summary

This design journal outlines the design process and concept development of an active device that enhances human capability in harsh terrains. Specifically in the activity of climbing, though it has diverse applications.

My interest in this materializes from the realm of cyberpunk-inspired gaming and being a climber myself.

The predominant objective of this project is to create a powered device that may aid humans in survival. To that end research was conducted into existing developments and current apparatus available in the activity of climbing.

Following this research, it was identified that most forms of exoskeletons or similar instruments were intended for military, medical, or construction utilization.

It was determined that fabricating an exosuit would be an appropriate solution for aiding climbers as it may incorporate functions of multiple existing equipment that are in use.

After discussion with a few expert and amateur climbers, the requirements of the device were set up and a prototype concept was created for review. Unfortunately, I was unable to contact rescue workers for comments.

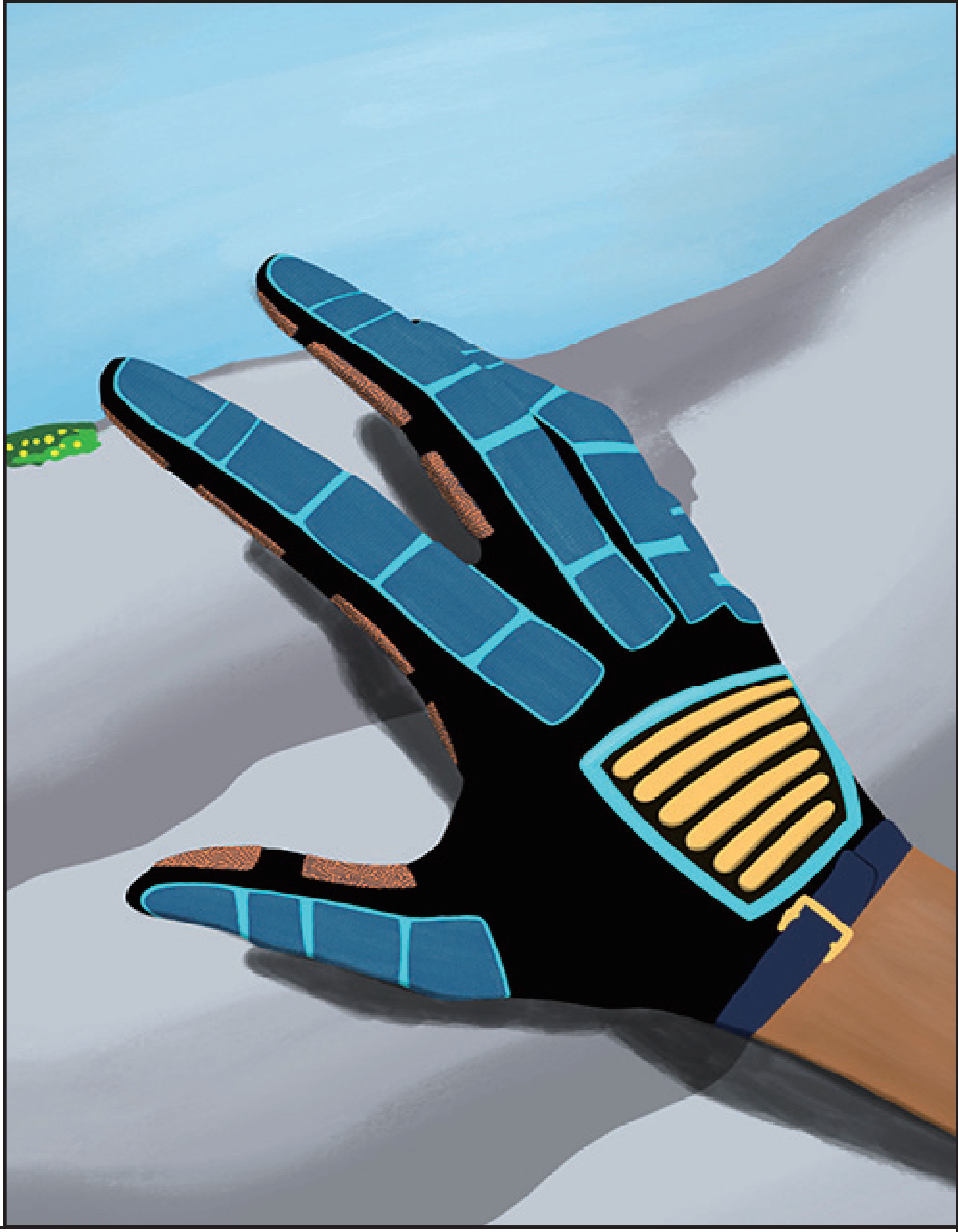
The technology to be used in the product was ascertained via pre-existing and further research into actuators and human anatomical structure.

A final prototype was created with improvements based on the recommendations received via review. Here inputs from peers and project guides were also inculcated into the design wherever possible. While a few suggestions were retained for future prospects.

User testing was not carried out as the current technology does not allow for the creation of a functional prototype.

However, feedback was taken and a scale model was created to illustrate the concept physically.

The product, hence called Juggernaut or glove or gauntlet, was deemed inadequate for climbers and alternative applications were discussed.



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Mural 2 - Conceptualization - https://app.mural.co/t/mscpdestudio/m/mscpdestudio/1660400041944/457c09ea3cb07bb5498f1ae4a04918ce615a489e?sender=ud00abf20be4dbedb3d1b4123
Mural 3 - The Branch - https://app.mural.co/t/mscpdestudio/m/mscpdestudio/1660400055630/daa1863a321c2041fa2ec1420f63af1cf884edbd?sender=ud00abf20be4dbedb3d1b4123

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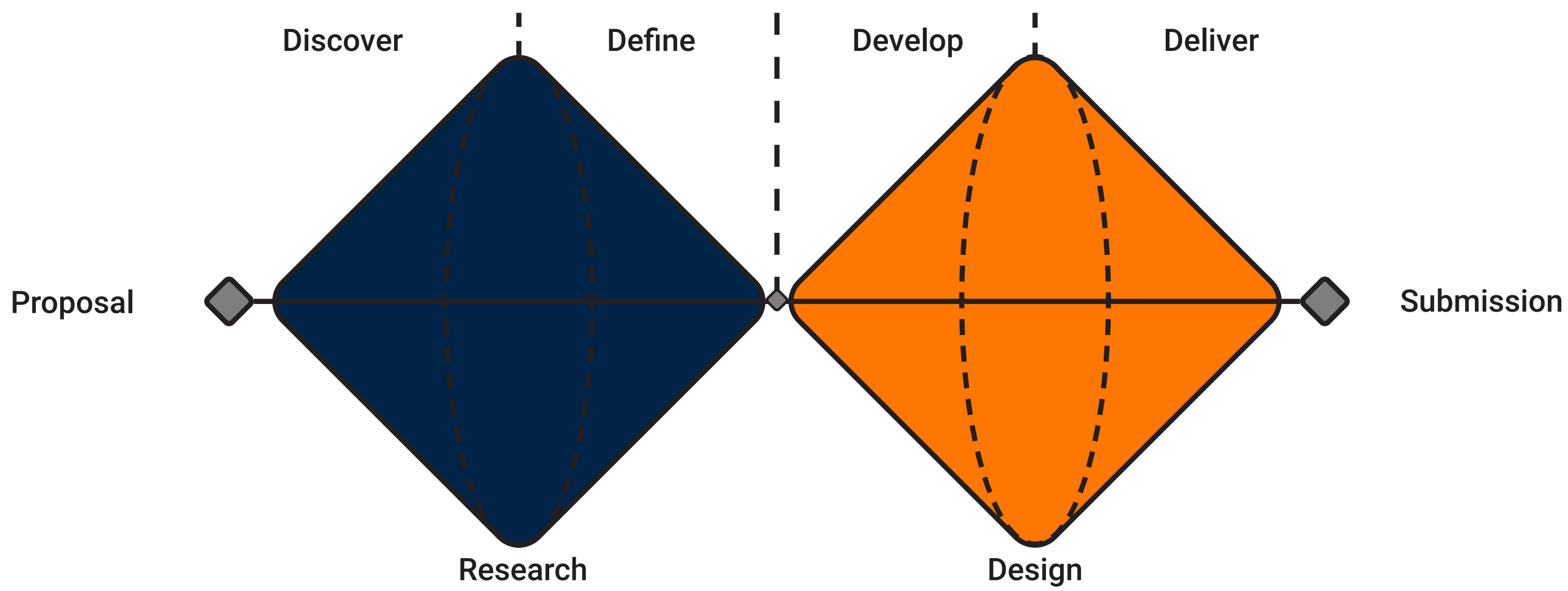


Discover
Define
Develop
Deliver
Proposal
Submission
Research
Design

Motivations and Inspiration

Human interest spans a vast horizon. There are so many endeavours we pursue that are so contrasting it is a marvel that one species is capable of such triumph. Akin to our achievements, each possesses disparate skills in diverse fields, some prodigious at a trade and some hopeless at the same. Though life provides bountiful opportunities for viable fields for enterprise, they are still measurable and possess a limit. To overcome such limits humans have aspired to develop and improve quality of life ad infinitum. Active devices are frequently used to such an end. For example, a mobile phone, considered essential by most today is an active device that enhances our life significantly.

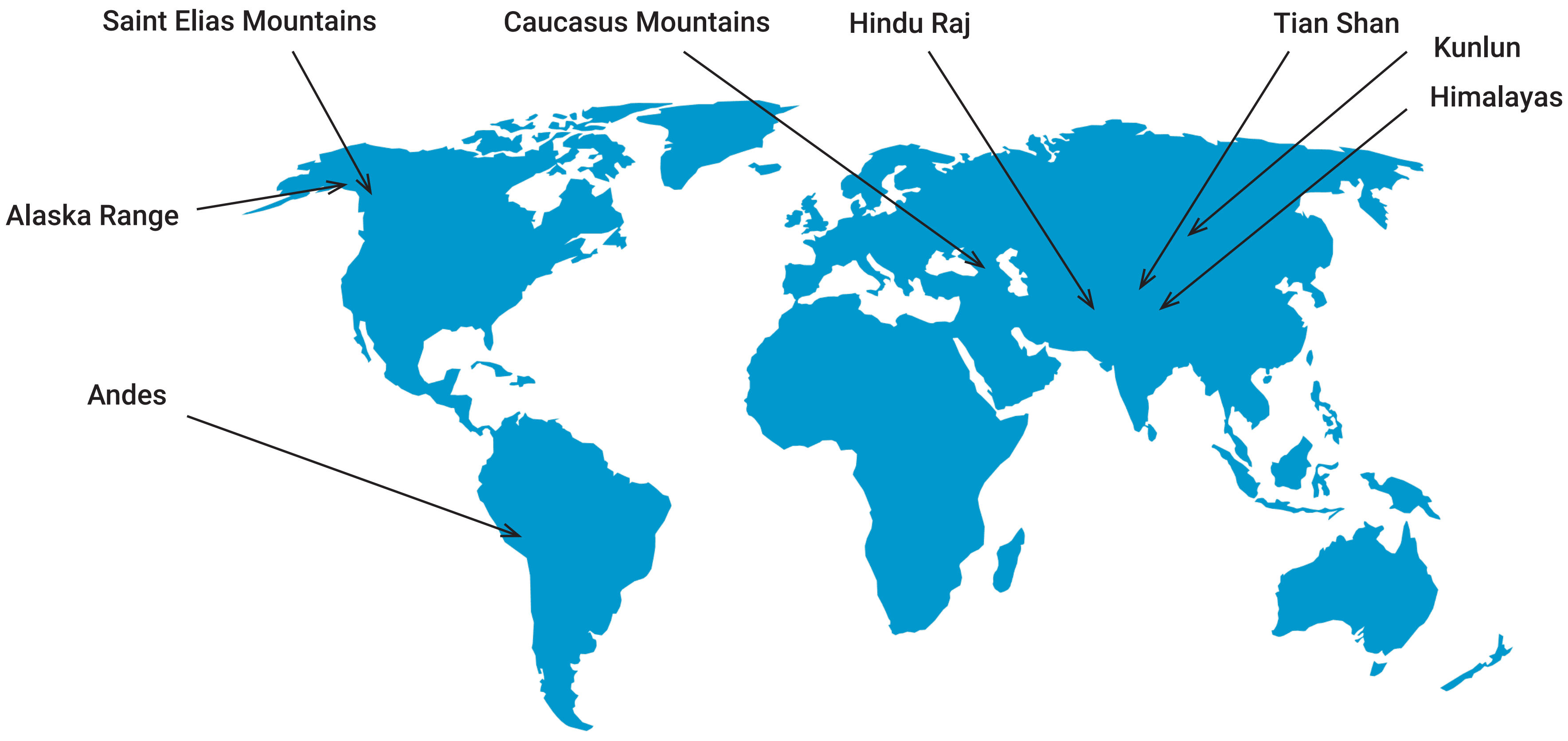
An active equipment to enhance human capability. An active equipment is one that is powered by an energy source in some form and uses that energy to perform a task. It could be any source, augmenting any human capability. Whether it be physical strength, sight, endurance, etcetera.

To research this domain I investigated 'Exoskeletons' and their development. Reviewing most forms of exoskeletons or prosthetics currently existing or being developed. While also studying the development up to existing designs.

With my existing interest in the improvement of arm strength augmentation, it was distressing to see minor advancement made in this section of the field. Most forms of exoskeletons had leg augments as the machine was quite heavy for the human body and needed to carry its own weight.

There are many companies working on leg efficiency to improve many aspects of walking such as bionic legs to help in rehabilitation, increase speed, delay fatigue, lift heavy weights without strain, and help physically disabled people move among others.

Mountain Climbing



Mountain ranges of the world

Opportunity

As an on and off climber, there are numerous occasions where I've been inspired by looking at experts daring to climb the highest peaks and wanting to climb one myself. Though due to the large sabbaticals between each climb the physical strength required to attempt such feats is beyond my capabilities. Such is also the situation with many amateur climbers, wherein injury, lack of time, or physical disabilities prevent aspirants from undertaking such ventures.

An active device that enhances human survivability in climbing may allow individuals such as these to pursue such ambitions. With their shortcomings augmented by the equipment the risk undertaken is substantially lower. I reviewed existing forms of climbing and the available equipment for the same. I realized most forms of aided climbing had equipment that had to be manually placed in position based on the expertise of the climber. The equipment were not robust and its success or failure was entirely dependent on the user, while also being cumbersome to use without considerable practice. Moreover, none were 'active' devices.

A climber tends to reach heights where any blunder may well prove fatal. Oxygen levels above 900m start thinning which leads to faster fatigue and gradually lower endurance. Furthermore, the fingers of an average human are not predisposed to lifting weights comparable to the human body weight. Expert climbers have to train for weeks or perhaps months to attain the necessary strength to safely climb.


Carabiner

Research

Internet research, interviewing climbers of various capabilities, actuator technologies, battery technologies, and control systems.

Museum visits -
- VA Museum visit - I spent an entire day visiting the only product design museum in the UK. Observing various forms of product design and discerning the sustainable outlook envisioned for the future of product design.
- Dundee Museum of Transport - Observed automotive technological advances throughout history. Realized the extent of battery technology and its future prospects.

The specific selection of each part of technology and the reasons behind the decisions are explained in the 'Broad classification of the parts of the glove' section of the technical report.

Brainstorming for ideas during tutorials with project guides and peers.


Silicone Artificial Muscle

User and Context

Users

The product is designed with a focus on climbers, while their needs are central.

However, it cannot teach a novice the fundamentals of the activity.

The ideal user is set to be an experienced climber, a climber who may be injured, or a climber involved in rescue efforts.

All of these personas will find the device described of use.

Though it may also be used in practice to improve the grip strength of new climbers or amateurs.

Context

Juggernaut is a glove that improves grip strength via artificial muscle augmentation. It is powered by a battery pack on the dorsal side of the hand.

The glove is not reversible, that is the right and left pieces cannot be interchanged.

It is expected to work independently and may not need a connection to other devices to work.

Juggernaut is expected to be used in harsh terrains or environments.

In that, it would have to be considerably durable and withstand most situations a climber may encounter. Such as snow, rain, grime, etc.

It would also need to be comfortable, as the user is expected to use the product during strenuous activities.

Benefits

A glove/gauntlet that improves grip strength would have abundant applications.

In the sphere of climbing, it is expected to improve the survivability of users by delaying fatigue as it improves endurance.

Climbers often need to hold their body weight on their fingers for extended durations. This activity is unusual to say the least in everyday life. This makes a repeated effort on part of the fingers acutely detrimental if untrained.

Here assistance would improve the endurance of a climber substantially, as often this is the weakest link in their arsenal.

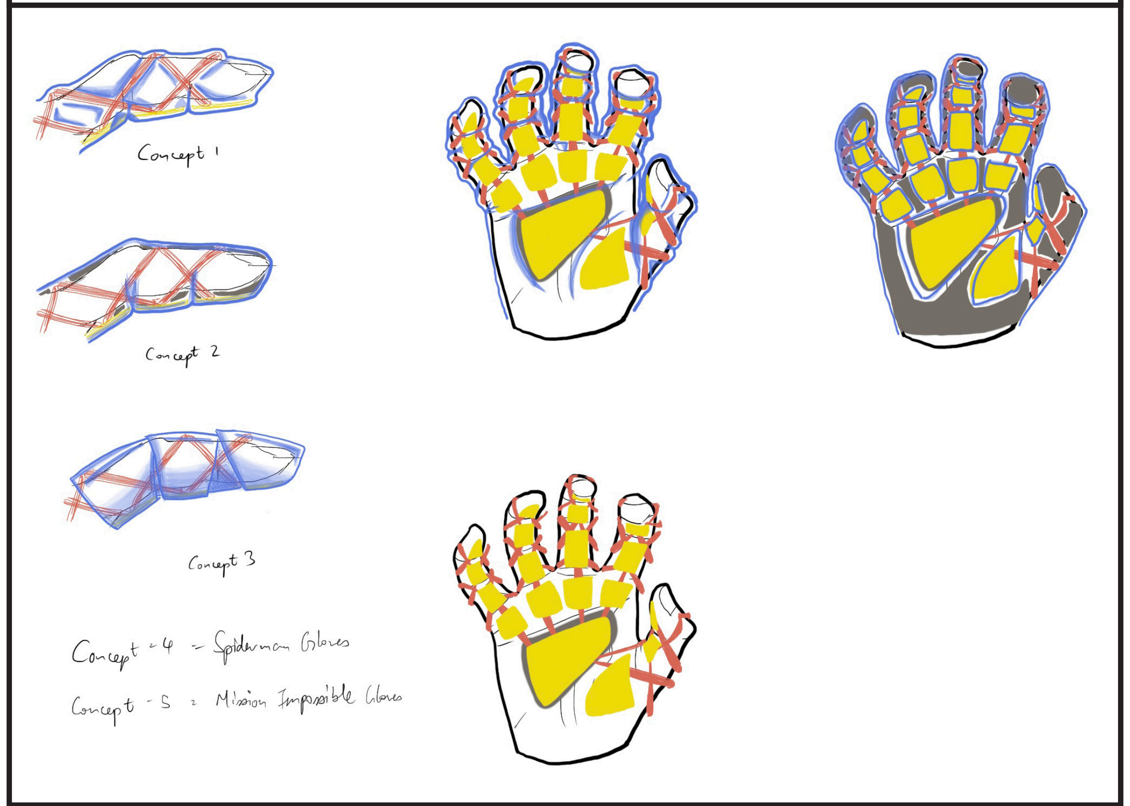
Moreover, the likelihood of injury lessens, leading to an exceptional user experience.

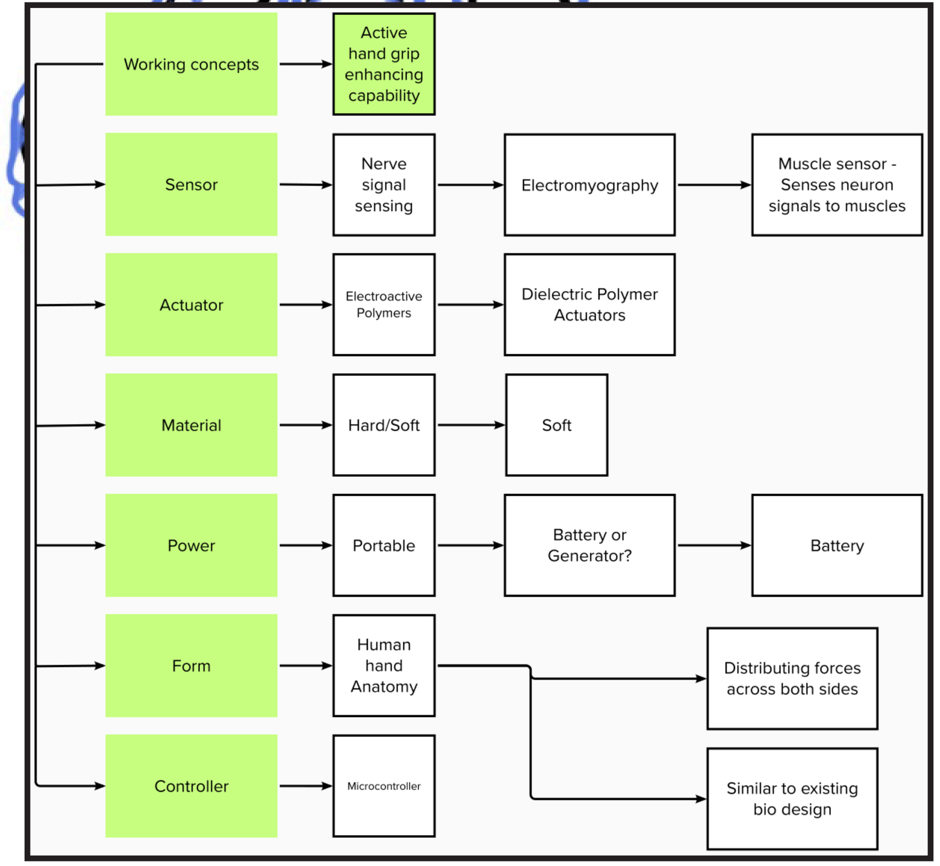
Over 900m altitude, the air starts thinning, which leads to fatigue faster. Most climbers reach at least over 1500m to the top. Here improving endurance would be advantageous.

Develop

Ideation and Conceptualization

Initial glove layer ideation





Swimlane concept ideation and prediction

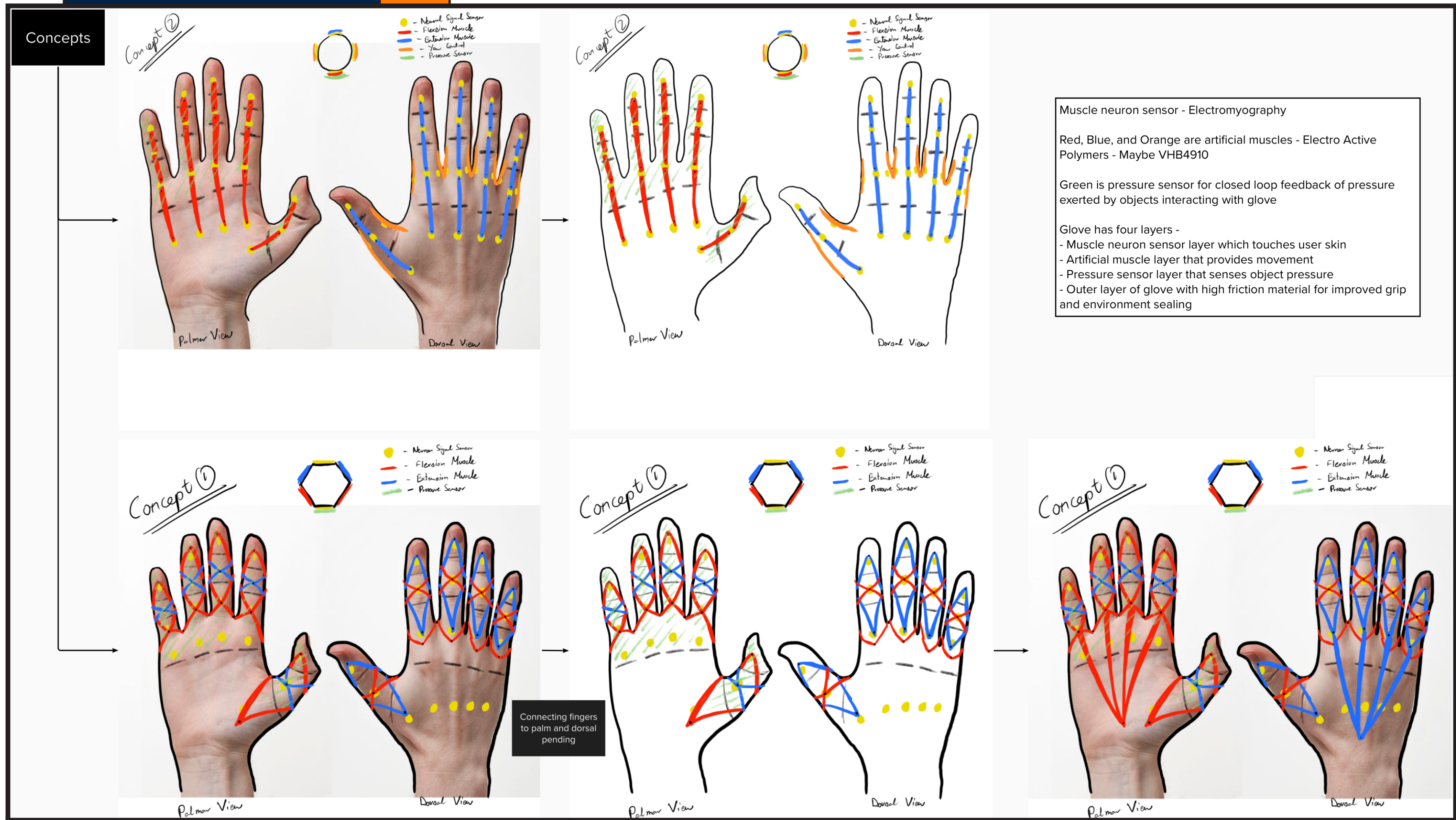
Initial concepts were created based on fundamental knowledge of what the glove may consist of and inspiration from existing aesthetics in high-performance gloves/ gauntlets from movies and video games.

The ideation was organized in layers, it was concluded from research all components will likely not fit within the same workspace and will need to be separated.

A hard shell design was put forward as it would provide a stable framework to work on for any soft or moving parts such as actuators.

Components of the glove were broadly classified into six categories - Sensor, Actuator, Material, Power, Form, and Control.

Each category was investigated separately. Initial thoughts and progression is illustrated in the swimlane diagram.



Actuator placement concepts

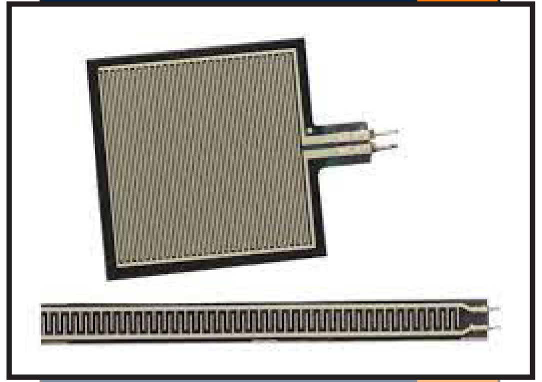
The glove would have to be specifically designed for each user as -

- The appropriate placement of sEMG sensors would be unique to each hand, though a larger sensor may overcome this issue.
- The rigid frame of the glove must be comfortable for the user's hand.
- The glove must fit snugly and firmly to prevent slipping of the glove. A wrist strap may prevent the glove from slipping off the hand entirely however the surface of the inner layer must not slip from its position.
- This will allow for consideration of allergies, and preferences of each user as opposed to one size fits all.

Biological inspired design

The artificial muscle actuator placements are inspired by existing biological human anatomy design and function in a similar agonist-antagonist pair.

Another concept where the forces were balanced between the two sides of a hand - dorsal and palmar sides - was also considered as this would reduce stress accumulation on one side of the glove.



Thin Film Pressure sensor

Used to sense pressure experienced by the hand due to environment

Creates a closed feedback circuit

Artificial Muscle

The primary component that aids in the movement of the glove

Soft material; Needs further research and development

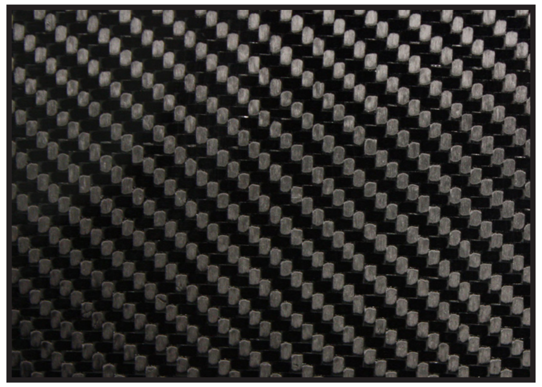
Surface Electromyography sensor

Detects muscle neuron signals non invasively

The primary driver of the glove

Haptic Feedback Module

Creates vibration feedback for any alerts that need the user's attention

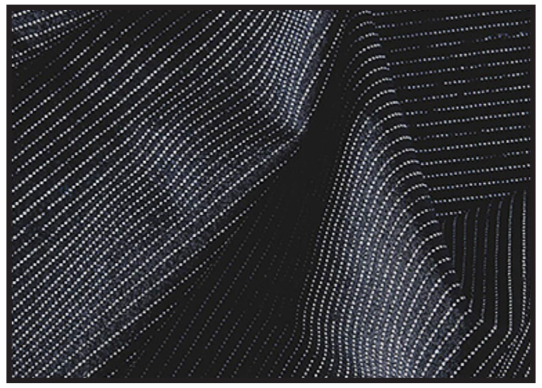


Carbon Fibre

Very high strength material

Used as the scaffolding in the glove

Provides shape to the glove



Dyneema

Extremely durable material

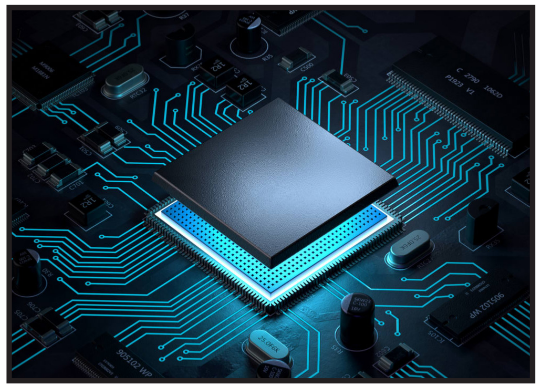
For durability of the glove

Water-resistant, Abrasion resistant, Piece resistant, and Breathable

Polyester

For the inner layer, a comfortable layer on contact with user's skin

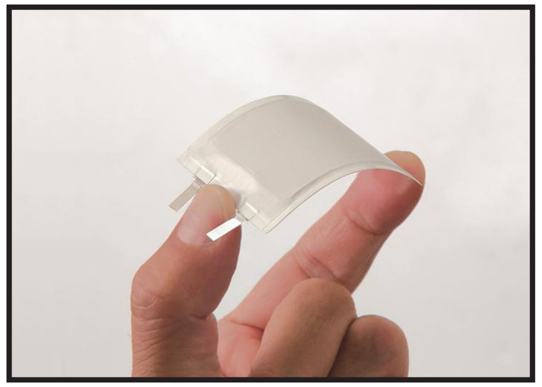
Breathable, durable, and Water repellent



Microcontroller

The control system of the glove

It is an embedded system that needs to be configured only once



Flexible battery

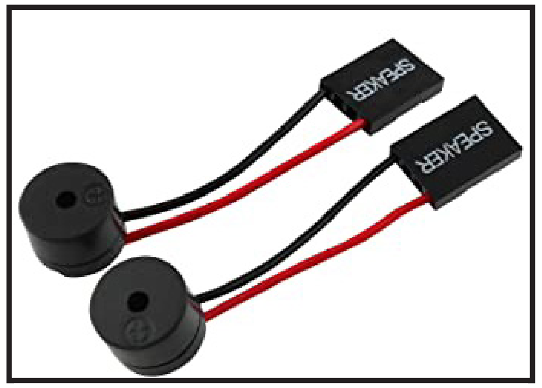
A power source that is flexible with very high energy density

Needs further research and development

LED

Light indicators displaying battery charge level for the user

Efficient illuminators

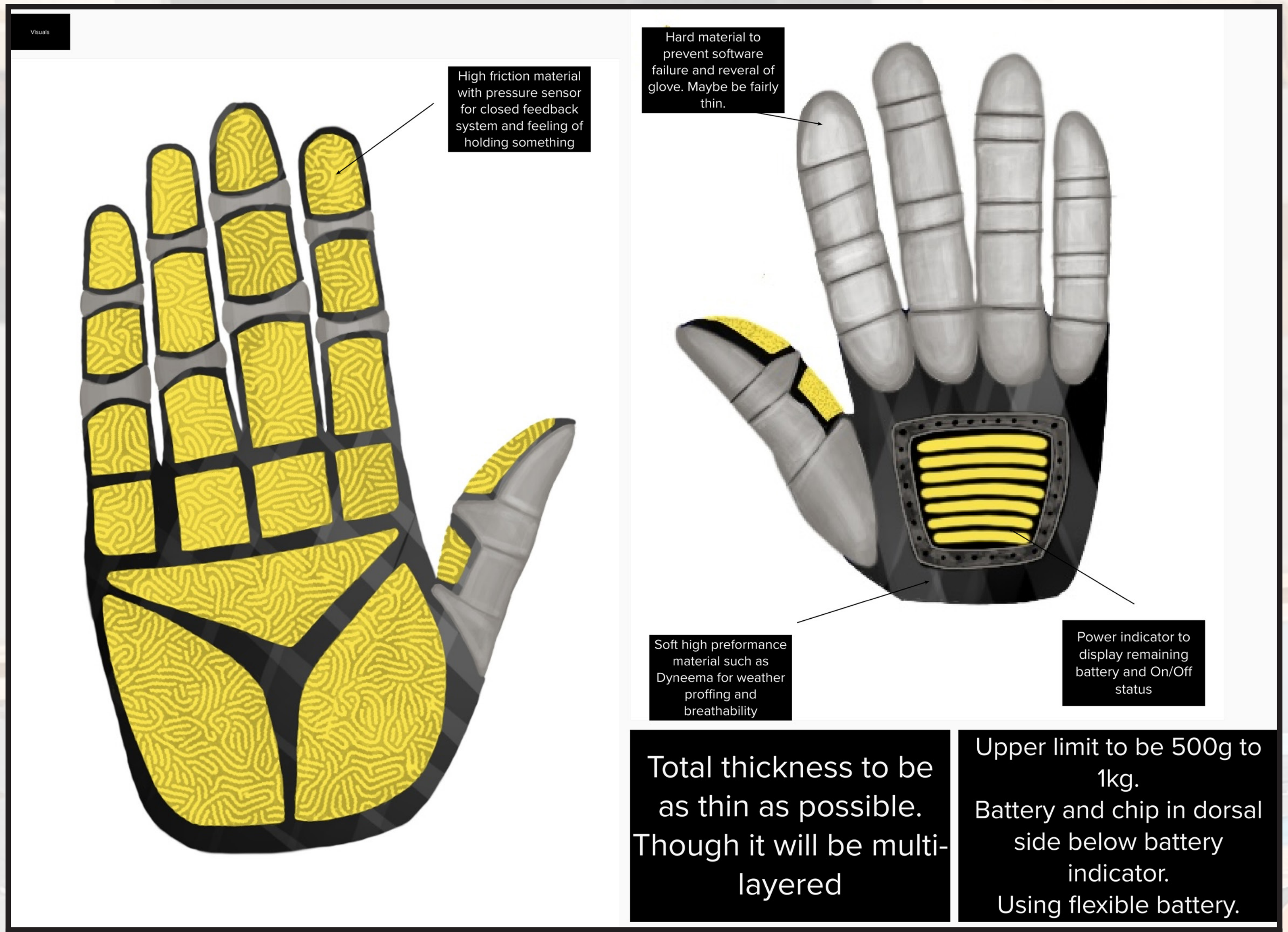


Speakers

Tiny speakers for audible alerts that need the user's attention

Such as low battery levels

Prototyping and Review



First Prototype

After interviews with climbers, the necessity of minute tactile feedback was realized.

This led to switching over to a softer 'exosuit' design with primarily soft parts while maintaining the least possible thickness of the glove.

Iteration One of Juggernaut from the 'Conceptualization' mural as illustrated on the left. With preferred performance requirements details that are mentioned in the image.

This design was the precursor to the final design later refined with a focus on improving performance. With the realization of newer aspects of actuators, that is, their expanding nature as opposed to contracting nature similar to biological muscles.

The upper metallic plating was added to prevent catastrophic inversion of the glove on the dorsal side due to software failure. Which would invariably lead to fractured bones and possible inability to further use the hand for the remaining duration of the expected life of the user.

The metallic plating must physically make it impossible for such an event to pass. Whilst simultaneously remaining as thin as possible to avoid restricting user movement.

Post the second interview with users and peers, the addition of a few more features was recommended.

The dorsal metallic plate was to be coated with gripping material to improve friction, as climbers often overlap their hands while climbing and this would aid in the process.

Furthermore, the addition of non-visual battery feedback was preferred in situations where the hand is not in view of the user. This was resolved by the addition of a haptic and audio feedback mechanism.

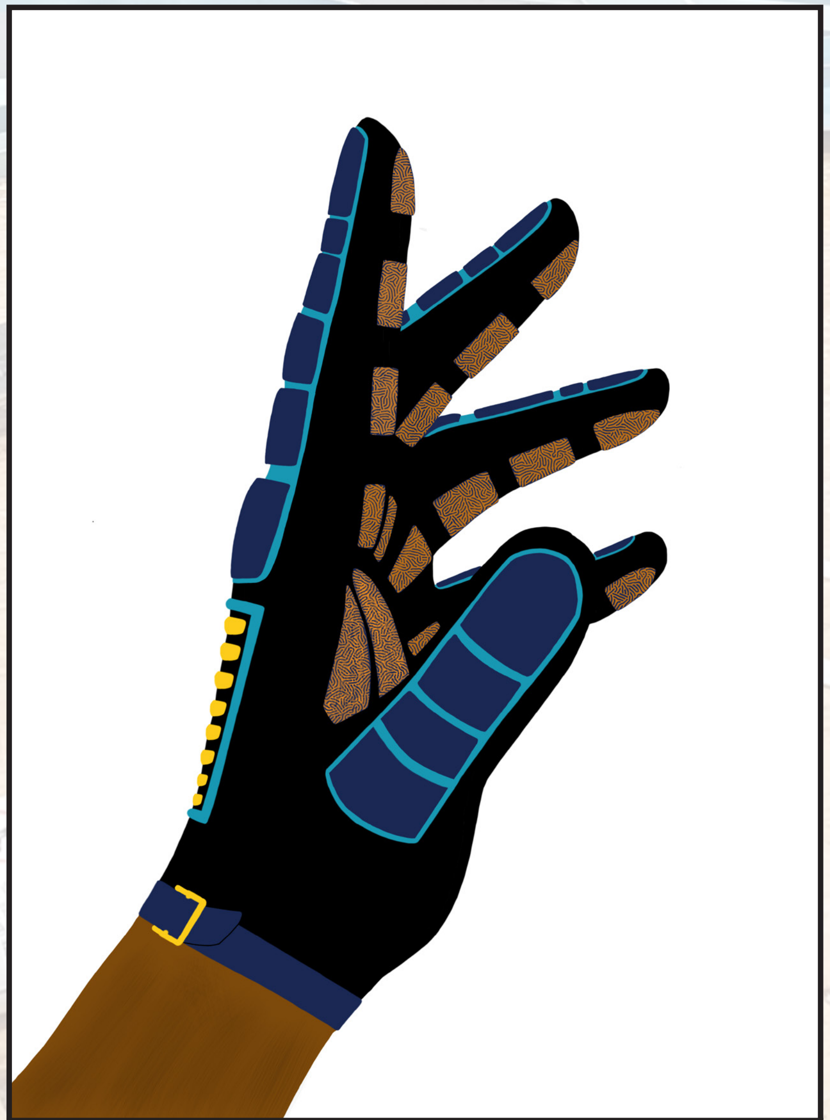
Additionally, interest was exhibited in wanting a display of the 'current percentage power being used' indicator that illustrates the stress on the glove. Though this was a purely optional preference.

A future consideration was proposed, wherein the glove could be powered by the movement of the user's legs. Though unfeasible for this product, it may be viable in a full-body exosuit.

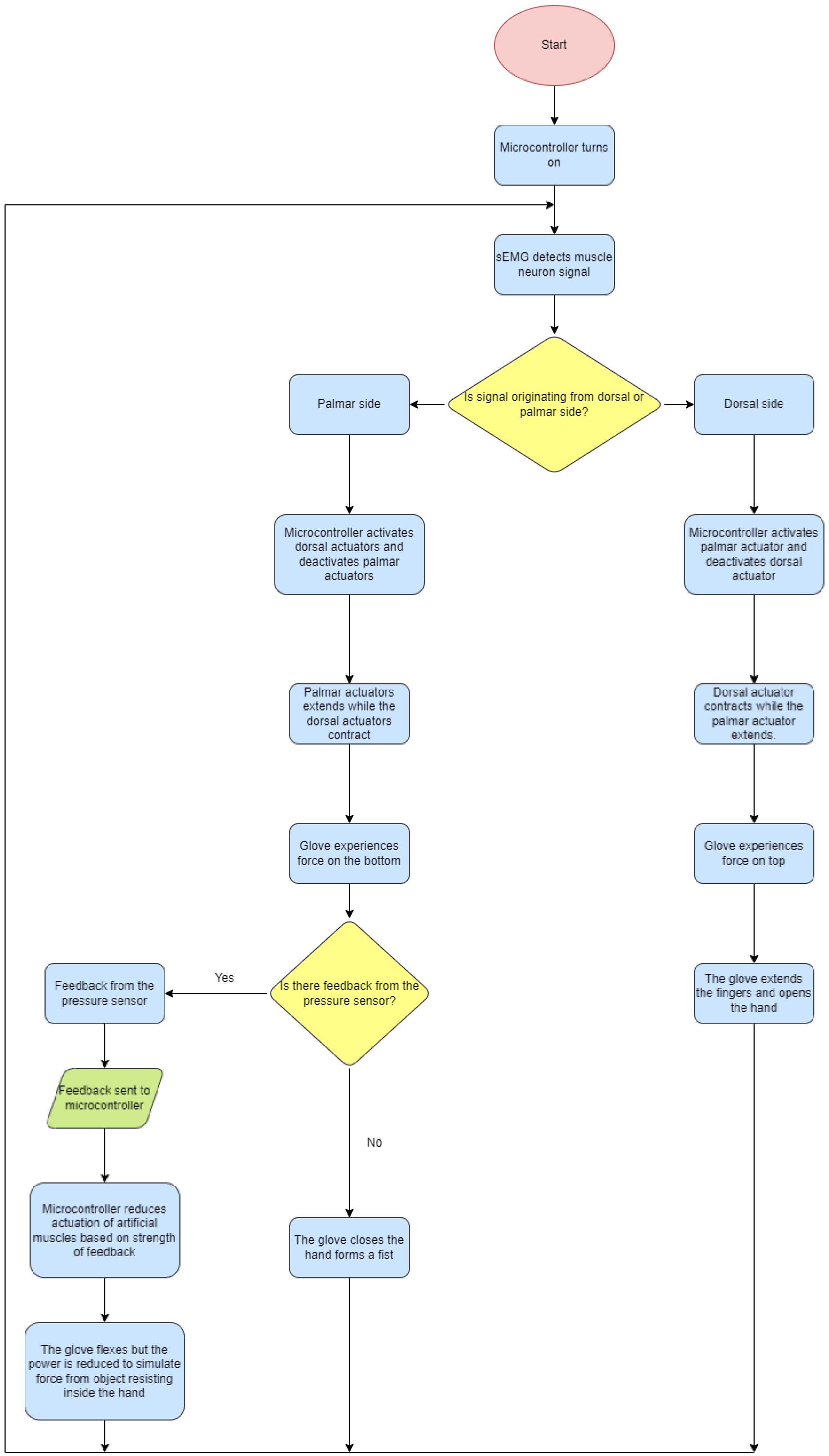
The final prototype is illustrated on the right side.

It illustrates the improvements over the first prototype. While also improving aesthetics.

It incorporates many of the suggestions desired by interviewees. Such as gripping material on both the palmar and dorsal sides. And various methods of battery level indication.


Final Prototype

How it works



This flowchart illustrates the steps during the operation of the glove.

The following are the steps of operation in condensed form -

Step 1 - Muscle neuron signal for activation is detected by the sEMG sensors.

Step 2 - The artificial muscle actuators respond why deactivating in the desired direction to contract while the antagonist pair fully activates to expand.

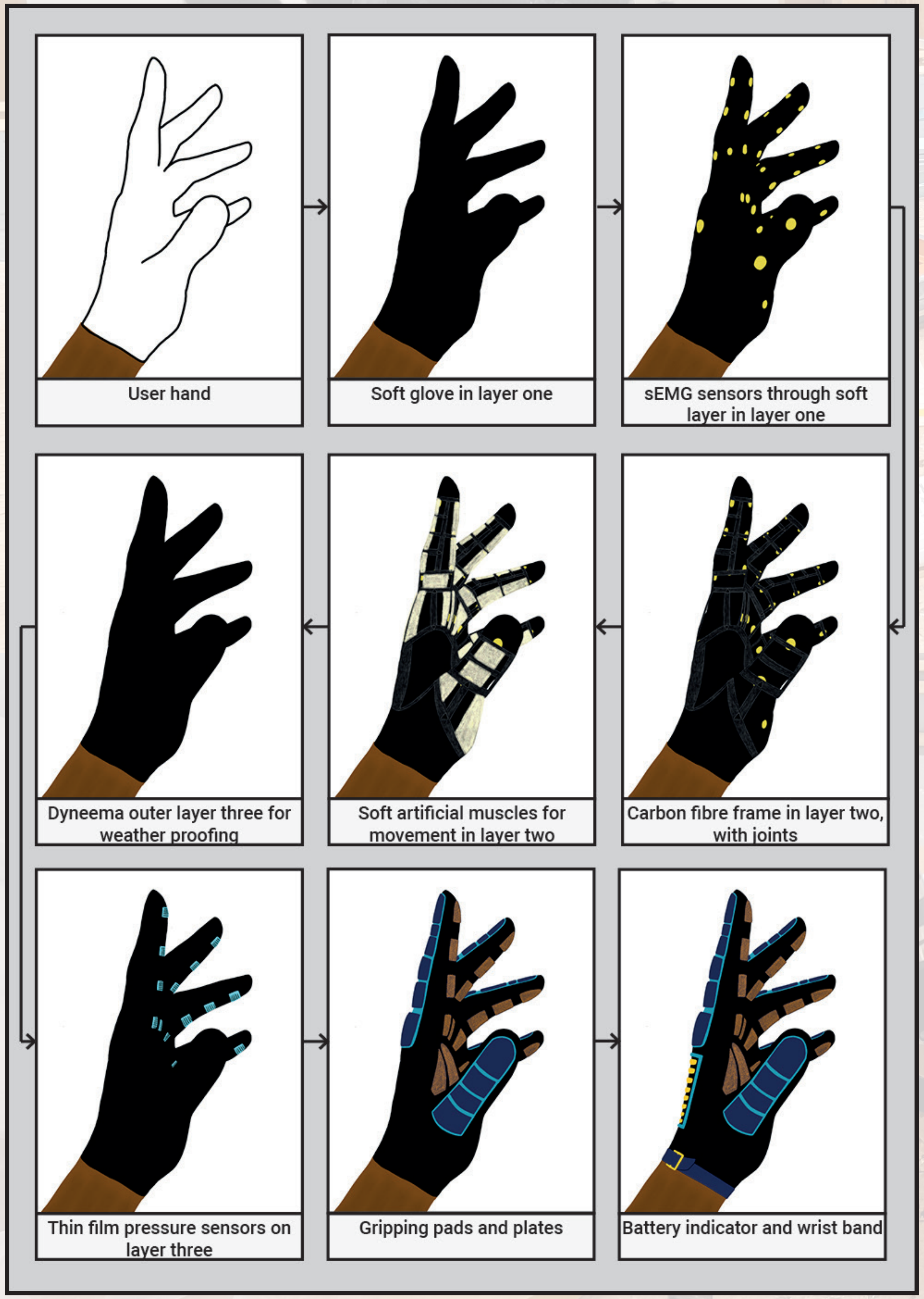
Step 3 - If the pressure sensors below the palmar pads detect resistive pressure from the environment on the glove, it will send a signal to the control system.

Step 4 - The control system will respond by reducing the deactivation of the agonist and the activation of the antagonist pair to simulate resistive forces on the glove.

Step 5 - This provides a 'feel' of the object held between the fingers inside the hand. And helps avoid crushing the object.

This process repeats constantly multiple times per second while the glove is operated.

Design Details



Layers and their progression

Glove layer configuration and elements

Layer One consists of materials that interact with human skin.

The materials have to be skin friendly and fit for long strenuous usage.

This layer fits snugly to the user's hand to prevent slippage and maintain appropriate sEMG contact.

Surface electromyography sensors are placed at key locations throughout this layer.

sEMG sensors are in direct contact with the skin.

Layer Two contains all of the mechanical movement-inducing components.

Artificial muscle actuators are placed at key locations as determined via human anatomical research and mentioned in the 'Glove layers and specifications' section in the technical report.

The actuators are placed on a rigid frame that provides the necessary scaffolding to produce movement.

The scaffolding incorporates numerous joints with specified degrees of movement to allow for the glove's function. It also provides space for printing circuits needed for powering any technology used.

The frame must be extremely thin and yet with very high strength to accommodate the working forces with appropriate safety.

The actuator thickness varies during use, which in turn alters the layer thickness during operation.

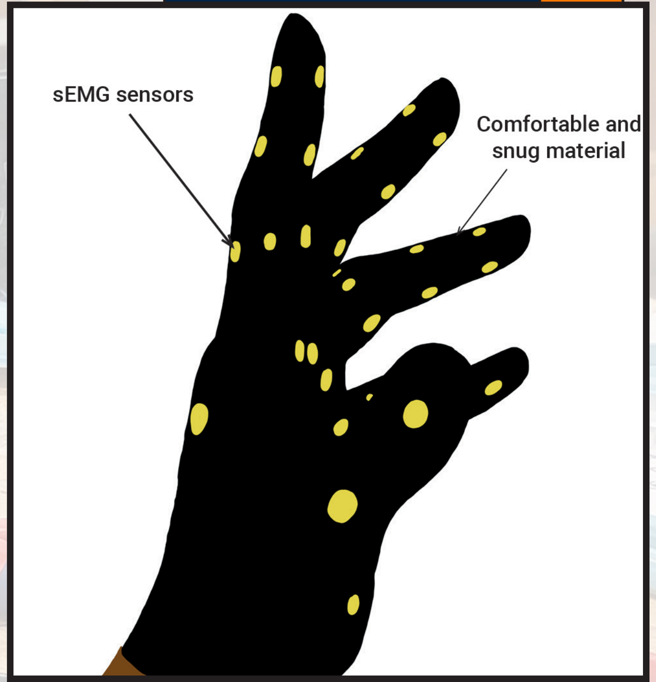
Layer Three executes multiple functions - aesthetics, friction improvement, safety features, and user interface. While also housing the power source and control system.

Juggernaut looks like a friction pad glove with a screen attached to the dorsal side.

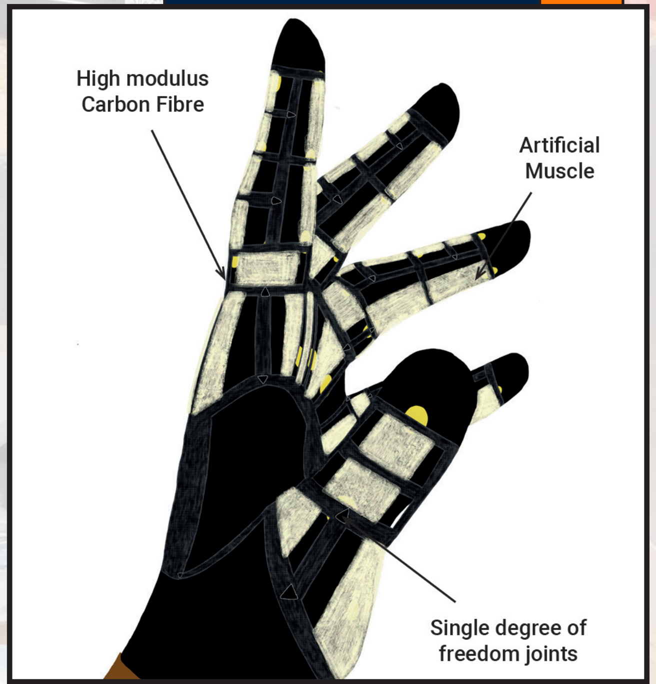
Gripping pads, on the palmar and dorsal sides, reduce the slippage of the glove with the interacting environment.

The metallic plates, pressure sensors, and wrist strap each play a role in safety - preventing glove inversion, preventing crushing objects, and slippage of the glove from user's hand respectively.

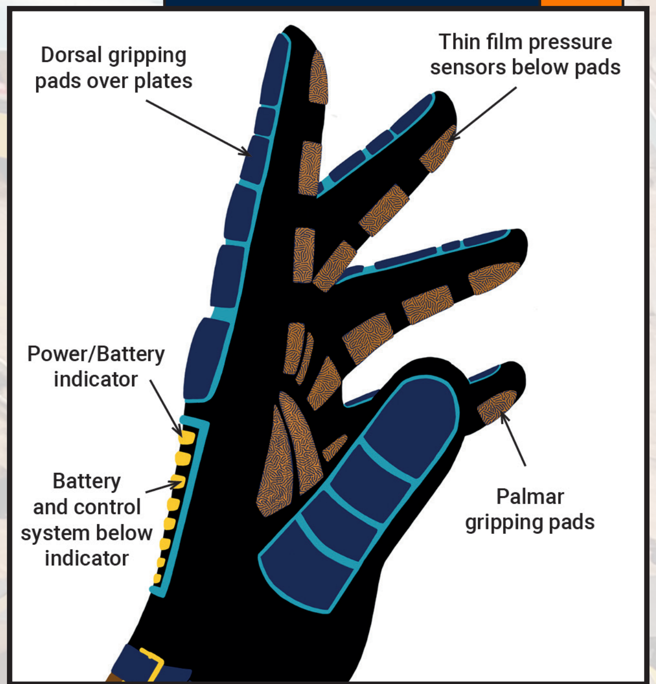
An indicator displays the remaining charge in the battery visually with LEDs. It also provides haptic and audio feedback when the battery is about to run out.



Layer One



Layer Two



Layer Three

Model Layout

Reflection and Way Forward

Reflection

This project has been a fun exploration, I've always wanted to work with exosuits. It taught me the depth of the field and that we are one breakthrough away from having such equipment. This project taught me what a design project can be. Throughout the project, I've felt like I was behind my peers due to my lack of reference for such devices as it is a 'futuristic' technology and there is never enough data on anything for adequate certainty. Nevertheless, I enjoyed the experience of working within and researching a field I'm passionate about.

Unlike the previous semesters, access to workshops for this one was not as restricted due to there only being Master's students for this semester. However, it was unfortunate that as students we had no singular place of study that could be accessed 24x7 as all of GSA buildings shut down for the night. Whereas GSA Halls study rooms are used as a storage facility by the staff. We had to find alternatives by regularly travelling to the University of Glasgow library.

In contrast, I appreciate all the aid provided by the tutors of GSA in guiding me through the project. I'm expressly grateful for the guidance of Craig Whittet and Jon Barnes this semester.

Way Forward

Juggernaut was pronounced inadequate for use for climbing as the glove is excessively thick and will not satisfactorily provide tactile feedback as required by climbers while climbing.

Furthermore, the technology described in this design is in its infancy and will need to be researched and developed further to be capable of adoption for use in the product.

Since the duration of the project was limited, the full work required to make it ready for production is not done. Neither has the optimization of parts been completed.

The future work on this device is technical and will require user testing as that was not possible at this time as the technology required is not available.

Nonetheless, there are numerous possible applications for Juggernaut as discussed in the technical report. They are also listed below -

- A hand rehabilitation glove – wherein the glove resists the motion of the fingers and the hand to improve the user's finger and grip strength by repeated resistive exposure to their fingers and hand.

- Industrial gloves – There are many applications in the industry – chemical and construction where improved grip is required while handling materials. Either due to the presence of lubrication which degrades the natural friction of the human hand or the existence of corrosive chemicals that inhibits the usage of natural grip.

- DIY tools – Augmented grip can prove to be quite beneficial while working with tools at home as the grips provided on the tool may be inadequate or worn out. While also performing the function of protective equipment.

Additionally, if the concept is extrapolated to create a full-body exosuit, recommendations suggested during interviews such as 'usage of the user leg movement to power the device' may be implemented into the product.

Juggernaut, active equipment that enhances the human capability of grip is a versatile tool that may be adapted for use in many distinct areas. Though with further development of artificial muscle and battery technology. Such a device could be mundane in the coming decades.

Reference

3M, n.d. 3M™ Gripping Material GM640. [Online]
Available at: https://www.3m.com/3M/en_US/p/d/b40069685/
3M, n.d. Micro-replication technology. Increasing holding power at work or play.. [Art] (3M).
A W Preece, H. S. W. J. L. G. E. C. H. M. M., n.d. Non-invasive quantitative EMG. National Library of Medicine.
Alexander Barnes, Q. L. G. Y. a. T.-F. L., n.d. Evaluation of Selected Dielectric Elastomers for use in an Artificial Muscle Actuator. The University of Adelaide, Australia.
Amane Koizumi, O. N. M. T. T. S., n.d. The Muscle Sensor for on-site neuroscience lectures to pave the way for a better understanding of brain–machine-interface research. ScienceDirect.
Bar-Cohen, Y., n.d. Artificial Muscles using Electroactive Polymers (EAP): Capabilities, Challenges and Potential. [Online]
Available at: http://ndeaa.jpl.nasa.gov
BBC News, n.d. Student died after falling 30m in Devon rock climbing accident. [Online]
Available at: https://www.bbc.co.uk/news/uk-england-devon-59307642
Bechtel, S., n.d. Endurance 3.0. [Online]
Available at: https://www.climbstrong.com/education-center/endurance-3-0/
Bernhard Hirt, H. S. M. W. R. Z., 2017. Hand and Wrist Anatomy and Biomechanics a comprehensive guide. s.l.:Theime.
Burrows, L., n.d. Soft Actuator Could Be 'Holy Grail' for Soft Robotics. [Online]
Available at: https://www.ien.com/product-development/news/20828749/soft-actuator-could-be-holygrail-for-soft-robotics
Center for wilderness safety, n.d. ALTITUDE SAFETY 101. [Online]
Available at: https://wildsafe.org/resources/ask/altitude-safety/oxygen-levels/
Cestus, n.d. Best Grip Material for Gloves: What Makes Gloves Grippy?. [Online]
Available at: https://cestusline.com/blogs/news/grip-material-gloves
Clancy, R., n.d. New artificial muscle technology for robotics. [Online]
Available at: https://electronics360.globalspec.com/article/16896/new-artificial-muscle-technology-forrobotics
Davis, N., n.d. Bionic legs and smart slacks: exoskeletons that could enhance us all. [Online]
Available at: https://www.theguardian.com/world/2016/dec/25/bionic-legs-and-smart-slacksexoskeletons-that-could-enhance-us-all
Drury, J., n.d. Exoskeleton research could allow paralyzed to turn and climb. [Online]
Available at: https://www.reuters.com/article/us-switzerland-exoskeletons-idUKKCN0SR1C220151102
Dyneema®, n.d. Dyneema® Fiber. [Online]
Available at: https://www.dsm.com/dyneema/en_GB/our-products/dyneemafiber.html#:~:text=Dyneema%C2%AE%20fiber%20is%2015x,resistance%20to%20chemicals%20and%20UV.
ELE Times, n.d. Microprocessor vs Microcontroller: What is the difference?. [Online]
Available at: https://www.eletimes.com/microprocessor-vs-microcontroller-what-is-thedifference#:~:text=Ultimately%2C%20microcontrollers%20and%20microprocessors%20are,that%20connects%20to%20external%20peripherals.
Freivalds, G. F. a. A., 1991. Ergonomics evaluation of a foam. The Pennsylvania State University, pp. 225-230.
GEORGE TORRENS, D. M.-P. &. A. N., 2001. Getting a grip. Ergonomics in Design.
Goe, P. B. a. A., n.d. Carbon Fibres: Production, Properties and Potential Use. Material Science Journal.
Hall, C. P. G. &. D. S., n.d. Prospects for lithium-ion batteries and beyond—a 2030 vision. Nature.
Hartman, K., n.d. Getting Started with MyoWare Muscle Sensor. [Online]
Available at: https://learn.adafruit.com/getting-started-with-myoware-muscle-sensor
Harvard Biodesign Lab, n.d. Soft Exosuits. [Online]
Available at: https://biodesign.seas.harvard.edu/soft-exosuits
Humphries, M., n.d. Elon Musk: Battery Energy Density to Increase 50 Percent by 2024. [Online]
Available at: https://uk.pcmag.com/infotainment-systems/128320/elon-musk-battery-energy-densityto-increase-50-percent-by-2024
Iain A. Anderson, T. A. G. T. G. M. B. M. O. a. E. P. C., n.d. Multi-functional dielectric elastomer artificial muscles for soft and smart machines. Journal of Applied Physics.
Iman Dianat, C. M. H. &. A. W. S., n.d. Methodology for evaluating gloves in relation to. Taylor and Francis.
K.K. Govarthanam, S. A. S. R., n.d. Technical textiles for knife and slash resistance. University of Bolton, Bolton, United Kingdom.
Lane, N., n.d. Pneumatic Indexing Drives for Automation. [Online]
Available at: https://fluidpowerjournal.com/pneumatic-indexing-drives-automation/
McKie, R., n.d. The robot suit providing hope of a walking cure. [Online]
Available at: https://www.theguardian.com/science/2016/nov/20/robot-exosuit-harvard-helps-strokesufferers-walk-again
Merletti, R., Rainoldi, A. & Farina, D., n.d. Surface Electromyography for Noninvasive Characterization of Muscle. American College of Sports Medicine.
Mihai Duduta, R. J. W. D. R. C., n.d. Multilayer Dielectric Elastomers for Fast, Programmable Actuation without Prestretch. Wiley Online Library.
National Park Service, n.d. Types of Climbing. [Online]
Available at: https://www.nps.gov/subjects/climbing/types-of-climbing.htm
Persun, T., n.d. Advancing Battery Technology for Modern Innovations. [Online]
Available at: https://www.asme.org/topics-resources/content/advancing-battery-technology-formodern-innovations
Press Trust of India, n.d. China's exoskeleton can help climb mountains with heavy weight. [Online]
Available at: https://www.business-standard.com/article/pti-stories/china-s-exoskeleton-can-helpclimb-mountains-with-heavy-weight-115082401244_1.html
Quach, J. H., n.d. Surface Electromyography: Use, Design & Technological Overview. Concordia University.
ReWalk, n.d. ReWalk: More than walking. [Online]
Available at: https://rewalk.com/
ROAM Robotics, n.d. Expanding Human Mobility. [Online]
Available at: https://www.roamrobotics.com/
Ross, D., n.d. Get more done: why now is the time to automate. [Online]
Available at: https://eandt.theiet.org/content/articles/2022/01/automation-welcome-introduction/
Sabir, T., n.d. Fibers used for high-performance apparel. Manchester Metropolitan University, Manchester, United Kingdom.
Sewport Support Team, n.d. What is Polyester Fabric: Properties, How its Made and Where. [Online]
Available at: https://sewport.com/fabrics-directory/polyester-fabric
Shuguang Li, D. M. V. D. R. a. R. J. W., n.d. Fluid-driven origami-inspired artificial muscles. Proceedings of the National Academy of Sciences of the United States of America.
Shunji SHIMIZU, M. S. S. S. Y. S. M. Y. A. T. Y. I., 1997. The Relationship between Human Grip Types. Monterey.
Tilsatec, n.d. Understanding Glove Coatings. [Online]
Available at: https://tilsatec.com/gb/news/understanding-glove-coatings
Volker Schöffl, A. M. U. S. I. S. T. K., n.d. Evaluation of Injury and Fatality Risk in Rock and Ice Climbing. ResearchGate.
Vollebak, n.d. Waterfallproof Jacket. The most waterproof and breathable lightweight rain jacket technology can build.. [Online]
Available at: https://www.vollebak.com/product/waterfallproof-jacket/
Wikipedia, n.d. Aid climbing. [Online]
Available at: https://en.wikipedia.org/wiki/Aid_climbing
Wikipedia, n.d. Artificial muscle. [Online]
Available at: https://en.wikipedia.org/wiki/Artificial_muscle
Wikipedia, n.d. HAL (robot). [Online]
Available at: https://en.wikipedia.org/wiki/HAL_(robot)
Wikipedia, n.d. Powered exoskeleton. [Online]
Available at: https://en.wikipedia.org/wiki/Powered_exoskeleton
Wikipedia, n.d. Transputer. [Online]
Available at: https://en.wikipedia.org/wiki/Transputer
WINKEL, C. F. &. J., n.d. Hand strength: the influence of grip span and grip. Taylor and Francis.
Wired, n.d. Stress Testing Real-Life Robot Legs | WIRED. [Online]
Available at: https://www.youtube.com/watch?v=CKvEBWaPd2I
Yi-Da Wu, S.-J. R. Y.-H. L., n.d. An Ultra-Low Power Surface EMG Sensor for Wearable. MDPI.
Zhihang Ye, M. S. S. F. R. A. Z. C., n.d. Artificial Muscles of Dielectric Elastomers Attached to Artificial Tendons of Functionalized Carbon Fibers. Wichita State University, Wichita