

A parametric approach to mass customised hand wearable cooling products to improve clinical efficacy for CIPN

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ABSTRACT: A parametric framework for personalised hand-wearable cooling devices is presented to optimise fluid and thermal performance using patient-specific anthropometrics. Iterative prototyping phases validated improved uniformity and efficacy. The approach bridges ergonomic customisation and thermal optimisation, enabling scalable, clinically effective wearable heat-exchangers for diverse patient populations. This study builds on prior work on personalised scalp cooling with Paxman, applying parametric principles to limb cooling for Chemotherapy-Induced Peripheral Neuropathy prevention.

KEYWORDS: mass customisation, healthcare design, ergonomics, anthropometry

1. Introduction

Chemotherapy-Induced Peripheral Neuropathy (CIPN) is a common dose-limiting side-effect of taxane-based chemotherapy, causing progressive and often irreversible pain/sensitivity in the hands and feet. Treatments for CIPN are not well-developed and urgently needed. Limb cryocompression during chemotherapy has demonstrated promising early data of preventing/reducing CIPN severity, through inducing thermoregulatory responses like vasoconstriction, induced through cold therapies. This novel approach to wearable cooling addresses an unmet clinical need, where our ongoing development of a dedicated CIPN-prevention limb cooling systems seeks to integrate a more customized approach, utilised in our scalp cooling (SC) products, proven to provide >80% efficacy through personalised fit.

The development of personalised wearable medical cooling devices requires patient-specific parameters, providing unique demands to achieve the efficiency required for thermoregulatory responses. This work presents a parametric design framework for hand-wearable cooling products that integrate CAD-based modelling to personalise device geometry from bespoke patient data. A mass customisation approach is successfully adopted in our previous SC studies, now applied for limb cooling for the first time, to bolster cooling efficacy through parametric rulesets to increase customisation, closeness of fit, and adjustability for varying global audiences. Utilising these approaches, the team was able to modify a predicate limb-cooling wrap to improve on clinical effectiveness for optimal heat extraction. liquid cooling systems, generally require a bladder where fluid channel depth, thickness, and topology can be modified according to individual hands, achieving bespoke fluid dynamic performance criterions. A personalised anthropometrics framework ensures improved ergonomic integration, usability, and thermal performance while maintaining scalability across diverse patient populations.

Wearable medical heat-exchanger devices designed to regulate patient temperature through direct contact with the skin require a complex interplay of engineering precision, human factors, and clinical performance optimisation. Though hand measures are well documented, and other wearable cooling applications are also explored in broader literature, when developing the limb-wearable cooling bladders, and cross-assessing the results from stage III clinical trials in America several gaps in knowledge were highlighted. Initially, the team determined that closer fit was required, fluid performance could be

optimised and improvements to thermal performance could be enhanced. As the designs addressed a novel, unmet clinical need, the latter 2 areas expand contributions to knowledge for wearable medical cooling products. For closeness of fit, the authors acknowledged that hand measures were well explored, but incomplete for clinical applications such as this. This research utilises a similar methodology the team adopted for SC, where similar challenges were identified and addressed, where the team sought to adapt those approaches for one wearable cooling area, to elicit significant benefits to safety and efficacy as with SC using a parametric design framework proposed. The proposed framework is informed by years of comprehensive multidisciplinary collaboration for providing an approach to personalised SC cap products with a commercial partner, Paxman Coolers, the global leading experts in SC, have recently developed a limb-cooling device (Figure 1). We aimed to apply findings to limb-cooling for CIPN to improve fit and cooling for global audiences in >65 countries.



Figure 1. Current limb-cooling bladder/ wraps and concept machine at Beta phase

2. Literature review

The clinical effectiveness of cooling devices typically depends heavily on how well the device conforms to individual hand geometry. Poor fit reduces contact area and increases thermal resistance, undermining heat extraction. The literature review was structured to synthesise over 60 high-quality sources, including more than 50 peer-reviewed research papers alongside industry-standard texts and recent publications. Inclusion criteria focused on studies exploring hand ergonomics, anthropometrics, wearable product design (e.g., safety equipment, gloves, medical applications), and global adult populations (18+, all sizes, genders, and ethnicities), while sources lacking methodological rigour, outdated measurements, or limited demographic relevance were excluded. Reputable and widely cited sources were prioritised due to the extensive and sensitive nature of anthropometric data, ensuring accuracy and reliability. Although substantial relevant data existed, a thorough comparative assessment was required to extrapolate key measurements, reconcile differences across studies, and integrate findings into a cohesive, up-to-date dataset. This process enabled fragmented data to be systematically cross-referenced and consolidated according to the study's inclusive global market criteria, ensuring the final compiled dataset was accurate, relevant, and representative.

2.1. Ergonomics and anthropometrics

Global variability is a principal challenge in designing wearable medical heat-exchangers requiring accurate up-to-date datasets to ensure that devices fit securely and function effectively. In a globalised market, designers must work with data that account for population differences in stature, limb proportions, and hand morphology, while recognising that outdated or region-specific datasets can lead to poor fit and reduced device efficacy. The lack of universally accepted, high-resolution anthropometric data for certain demographics continues to present a barrier to optimal design, particularly in the medical contexts where device performance may be closely tied to anatomical conformity, like in SC (Unver et al., 2022), demonstrating that personalised wearable cooling caps were essential to improve efficacy to over 80% through personalised, improved fit, with optimal contact for varying demographics.

Research on human hand dimensions consistently shows that hand size varies by sex, age, and population group, with sex being the strongest and most stable predictor. Most studies note that the dominant hand tends to be slightly larger and stronger. Because of this broad variability across sex,

nationality, and age, ergonomics and wearable-device design guidelines generally recommend sizing medical or consumer hand-worn products to accommodate users from roughly the 5th-percentile female to the 95th-percentile male, ensuring most of the population is covered despite differences across races, regions, and age. As populations change due to demographic shifts, lifestyle changes, and global health trends, outdated measurements may compromise the fit, safety, and efficacy of devices (Binder et al., 2022). After an extensive literature review, collating available data, a selection of crucial reputable sources was used for the assessment Rogers et al., 2008; Buchholz et al., 1992; Griffin et al., 2018; Dianat et al., 2018; Yang et al., 2021; Oviedo-Trespalacios et al., 2016; Wang & Cai, 2017; Lee & Jung, 2015). The review identified gaps and discrepancies between sources, requiring a further 50 peer-reviewed publications to confirm accuracy from recent sources and fill gaps in knowledge for morphological sites to aid the close fitting design for global audiences. As highlighted, these discrepancies can be largely attributed to out of date historical sources that don't account for global shifts in human data from the past few decades. Findings below will highlight only the key hand measurements for Medium/ Average sized hands (Table 1), though all other measures for other sizes have been presented in the above literature review and other studies, collating global hand measures for varying ethnicities and demographics.

Table 1. Table of useful literature on hand measures

	50th Percentile (medium)	Avg. (Male & Female)	Dimension
Hand Length ♂	190mm	182.5mm	M = 182.5mm
Hand Length ♀	175mm	Range 182.5-175	
Hand Width ♂	104mm	97.5mm	M = 97.5mm
Hand Width ♀	91mm	Range 97.5-91	
Finger Width ♂	86mm	81mm	M = 81mm
Finger Width ♀	76mm	Range 81-76	
Hand Circumference ♂	215mm	209mm	M = 209mm
Hand Circumference ♀	203mm	Range 209-203	
Finger Length ♂	83mm	80mm	M = 80mm
Finger Length ♀	77mm	Range 80-77	
Thumb Length ♂	51mm	49mm	M = 49mm
Thumb Length ♀	47mm	Range 49-47	
Palm Length ♂	107mm	102mm	M = 102mm
Palm Length ♀	97mm	Range 102-97	
Hand Height ♂	51mm	48.5mm	M = 48.5mm
Hand Height ♀	46mm	Range 48.5-46	

2.2. Parametric design and mass customisation

Initially a comprehensive literature review on parametric design (PD) for wearable SC products was been completed for the personalisation of a head worn heat exchanger (Binder et al, 2024). This previous study enabled the team to convert findings from scalp to limb, simplifying it for a mass customised (MC) rather than personalised approach. From this, design parameters and test protocols were established using the collected literature on hand ergonomics and anthropometrics in Section 2.1 (Table 1), providing a list of core parameters that will make up the parametric framework in CAD. By integrating ergonomic considerations with material science and parametric modelling, we seek to address both the functional and comfort-related demands of wearable thermal medical devices. Research shows that PD for wearable design is well explored for the face, breasts, and hands, though other areas like the head, shoulder, torso, arms, legs, and feet, which can pose different fit challenges (Tian, 2025), have limited exploration for various disciplines. These approaches enable medical SMEs the ability to cater to wider audiences whilst providing more tailored devices for improved efficacy of clinical outcomes through personalisation. PD has become a powerful pathway for medical wearables, supporting MC, rapid iteration, and integration with simulation (Le et al., 2017). In healthcare research such as orthopaedics, parametric and generative workflows translate patient scans into device geometries (Chen et al., 2016). These complimentary

approaches, have demonstrated the ability to generate custom wearables, produced through additive manufacturing (Djokikj & Kandikjan, 2020). PD strategies are now being applied to head-worn medical cooling (Binder et al., 2024), where fit is the primary driver of efficacy. A CAD-based framework uses cranial anthropometric parameters to generate individualised cooling cap shells and channel networks (Binder et al., 2023).

SC studies show that anatomical fit strongly influences cooling rates, and therapeutic outcomes (van den Hurk et al., 2019). Tighter and more uniform contact has been linked to higher success rates in hair preservation during chemotherapy treatments, motivating research into personalised or semi-customised cooling caps that follow individual cranial curvature more closely (Nangia, 2018). Studies on wearable thermoregulation technologies similarly concluded that better mechanical coupling, individualised zone placement, and tailored fit improve both physiological cooling responses and subjective comfort (Georgievska et al., 2025). Cooling vests designed with user-specific sizing or adjustable cooling-element distribution have shown improved skin-temperature reduction, reduced thermal strain, and enhanced task endurance (Morris et al., 2021). Customising wearable cooling systems introduces practical limitations, user scanning, parametric modelling, variant testing, regulatory documentation for multiple configurations, and more complex supply chains. Nonetheless, advances in additive manufacturing, modular cooling channels, and automated fit-mapping workflows continue to reduce these barriers (Ramanathan & Gunasekaran, 2014).

3. Method

This study adopts a hybrid methodological framework combining Design Science, Design Thinking, and Reflective Practice to develop and evaluate a wearable thermoregulatory device. Design Science Research structures the artefact creation and iterative validation process, Design Thinking informs empathetic problem framing and solution development, and Reflective Practice supports critical assessment and refinement throughout the project. The theoretical foundation integrates ergonomics, anthropometrics, and thermoregulatory science to ensure dimensional compatibility, physiological relevance, and performance feasibility. The study applies both User-Centred Design (UCD) and Human-Centred Design (HCD) in distinct but complementary ways. UCD focuses specifically on cancer patients predominantly female to narrow and simplify the case study, enabling targeted evaluation of comfort, usability, and treatment-related sensitivities. Medium-sized hands were selected as the reference case for CAD review to standardise geometric assessment. In contrast, HCD informs the broader inclusivity framework, ensuring the design logic and parametric system remain adaptable to a global adult population (18+, all sizes, genders, and ethnicities).

A three-phase evaluation approach was implemented. Phase one simulated heat extraction under idealised conditions to establish theoretical performance benchmarks. Phase two examined a predicate medical device currently used in clinical trials to establish a clinical and functional baseline. Phase three conducted comparative analysis against the proposed parametrically optimised design. Geometry was developed using 3D scanning and rigged in Blender to refine ergonomic fit within CAD, while wearable liquid bladders were prototyped using RF welding for validation testing. This integrated methodology enabled systematic comparison, optimisation, and performance validation within a clinically informed design framework.

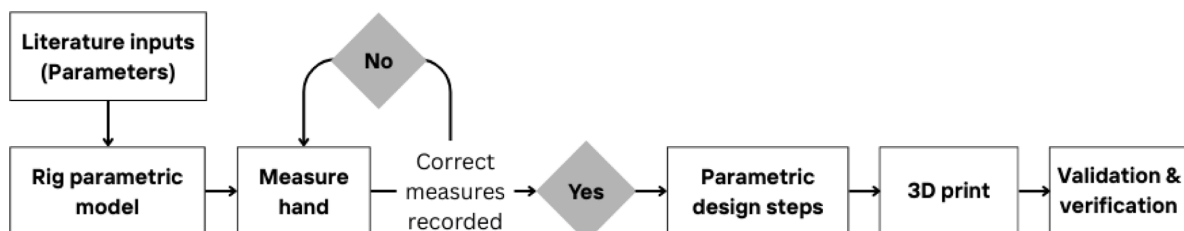


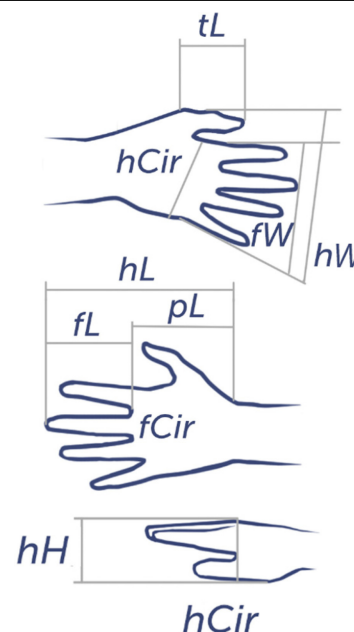
Figure 2. Framework utilised for parametric adjustment of the hand wearable products

To generate viable PD outputs, 4 standard hand models are proposed based on literature. A standard hand scan model is added to a workspace in Blender 4.2 and manipulated using a set of defined crucial parameters (Figure 3) from literature. The use of standard hand models, personalised to bespoke geometry, is more feasible and viable than generation of completely new geometry for each patient.

This will ensure consistency of crucial factors such as the cooling channels' cross-sectional volume for flow, wall thickness, and technical parameters of the cap which are maintained for safety and efficacy.

Table 2. Key hand measurements, with key showing framework for parametric hand adjustment for limb cooling, according to literature

Parameter	Parameter	Instructions
Hand Length	hL	Measured from the wrist to the tip of the middle finger.
Hand Width	hW	Measured across the widest part of the hand (usually the knuckles).
Finger Width	fW	Measured across the width of the fingers from the outermost external side of the Pinky finger and the outermost part of the index finger.
Hand circumference	hCir	Measured around the widest outermost part of the palm.
Finger Lengths	fL	Measured from the longest finger from the base of the knuckle to the tip of the middle finger.
Thumb Length	tL	Measured from the base of the knuckle to the tip of the thumb.
Palm Length	pL	Measured from the wrist to the base of the middle finger.
Hand Height	hH	Measured from the outermost part of the top and bottom of the hand.



4. Case study

As discussed in the methods section a comparative study will establish a benchmark for energy extraction using a predicate limb-cooling device and a parametrically modified improved limb cooling device, enabled through PD and MC framework in Blender. From this, an R&D team can iteratively rapid prototype outcomes in-house with manufacturing facilities, to enable subsequent validation and verification steps for measuring the success of design improvements proposed from this framework. Scan-to-3D packages in SolidWorks converted Revopoint low-resolution 3D scan data to create a library of hand models that could be rigged for parametrisation. SolidWorks equations were explored in, but the teams quickly realised that more organic modelling tools were needed such as Blender, where each knuckle and finger could be rigged for more efficient MC. This work follows the previous studies conducted on SC (Binder et al., 2024), applying the key parameters proposed in literature (Figure 3). 20 hands were scanned in Huddersfield (UK) based on the selection criteria highlighted in the methods section, providing a library of CAD data for the case study. From this, 3 hand models were produced in accordance with the 5th, 50th and 95th percentile hands, providing the models that individuals hands can be modified from in the case study. Using the proposed PD approach, these hands are scaled according to the outlined parameters shown in Figure 3 and Table 2, enabling the team to configure the 3D data based on patient measurements.

To establish a baseline for the parametric framework, a series of guide pillars were first positioned according to the predefined anthropometric parameters for a 50th-percentile average hand. The hand mesh was then sculpted to conform precisely to this default configuration, ensuring that subsequent geometric adjustments would remain grounded in anatomically representative proportions. These guide pillars served as the foundational control geometry, enabling a clear correspondence between the physical dimensions of the hand and the adjustable features of the digital model. Pillars were rigged with minimum and maximum limits governed through a system of property-based drivers, in which each driver once assigned to a specific parameter automatically constrained and controlled its associated value. With the guide pillars fully configured, shape keys were applied to the hand mesh, allowing continuous and anatomically consistent transformations across the defined parameter space.

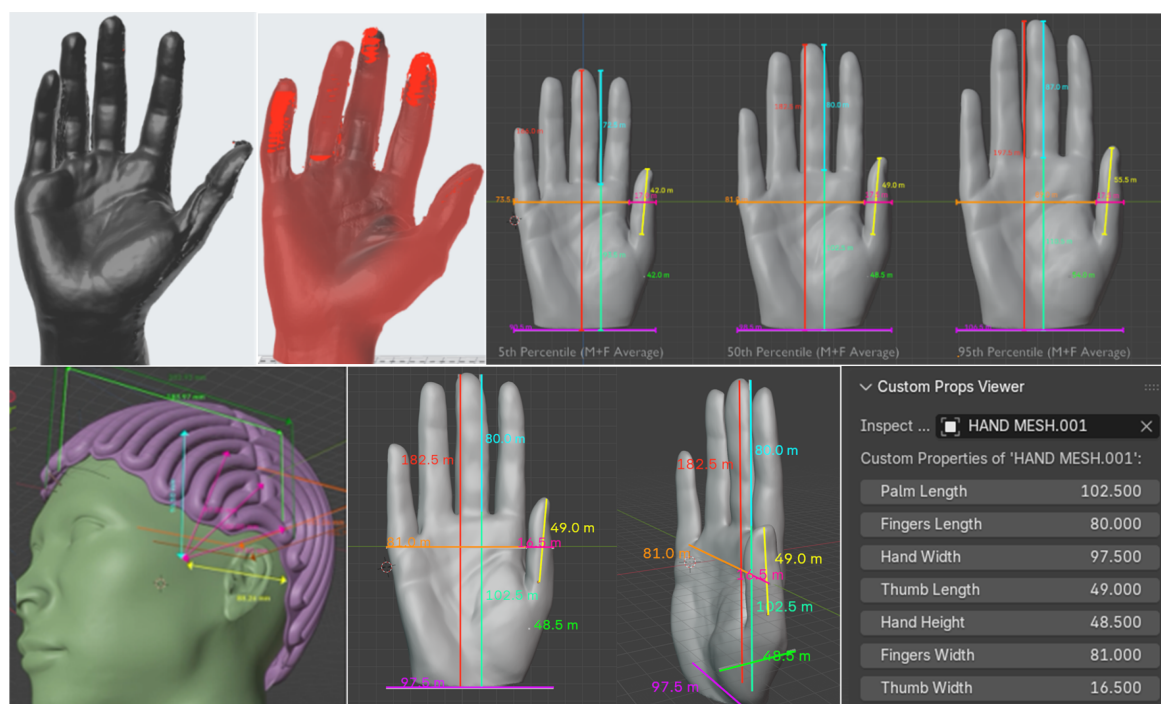


Figure 3. 3D scanned hands (top left), 5th, 50th and 95th rigged hands (top right), parametric approach on scalp cooling (bottom left), applied to hands for limb cooling (bottom right)

The proposed rig (Figure 3) forms the central mechanism for linking anatomical inputs to bladder geometry and, to thermal fluid performance. The rigging begins by ingesting patient-specific hand data either through manual measures or 3D scan data using these parameters to automatically regenerate the baseline hand mesh via drivers and shape keys. Each editable parameter in our pipeline is represented by a pair of complementary shape keys one positive and one negative which correspond to the anatomical extremes for that measurement. This paired shape key approach lets the mesh interpolate smoothly between anatomically realistic end-cases while preserving topology and local surface detail. In practice, the maximum and minimum limits for each measurement are not set by manually dragging the shape key sliders but instead are controlled by drivers attached to those sliders. To make the system value-driven (absolute) rather than purely relative, drivers are typically implemented using scripted expressions or simple mathematical mappings so that an input property (e.g. measured circumference or a normalized anthropometric scalar) maps deterministically to the appropriate shape-key influence. Scripted expressions and driver variables in Blender permit clamping, conditional logic, and transforms (for example min, max, scaling, or piecewise expressions), which is why an equation-driven driver is often necessary to ensure repeatable and predictable geometry across users.

The parametric rig developed for the hand model offers a foundation not only for shaping the wearable envelope but also for optimising the internal cooling bladder according to user-specific thermal requirements such as channel depth for flow, anthropometrics for surface area and material thickness for greater heat exchange performance. By parameterising key anatomical and functional variables, the bladder geometry can be procedurally adjusted to match an individual's hand dimensions, local curvature, and predicted heat-flux distribution. This is particularly relevant when designing polymeric or fluid-filled bladders that operate under Fourier's law of heat conduction, where conductive performance is influenced by the thickness of the interface, the surface area in contact with the skin, and the spatial relationship between temperature gradients and heat paths. The parametric representation allows elements to be tuned, like localising thinner regions, expanding high-contact zones, or reconfiguring coolant pathways so the design systematically reflect the thermal demands dictated by the user's anthropometry. The parametric rig's ability to generate constrained shape variations through drivers and shape keys, the system provides a means to automatically re-derive bladder geometries for a wide range of patient-specific parameters while preserving manufacturability and consistency.

Following the adaptation of wearable PD from SC to limb cooling in a commercial setting, further work will evaluate the application for the soft goods, to be applied to the insulating covers used in conjunction

with scalp and limb cooling and adaptation for other areas of wearable cooling. Figure 4 highlights how the adapted approach can be used to generate customised liquid bladders from bespoke patient data. Where a cover for the bladder could also be linked to the geometry of the adjusted bladder.

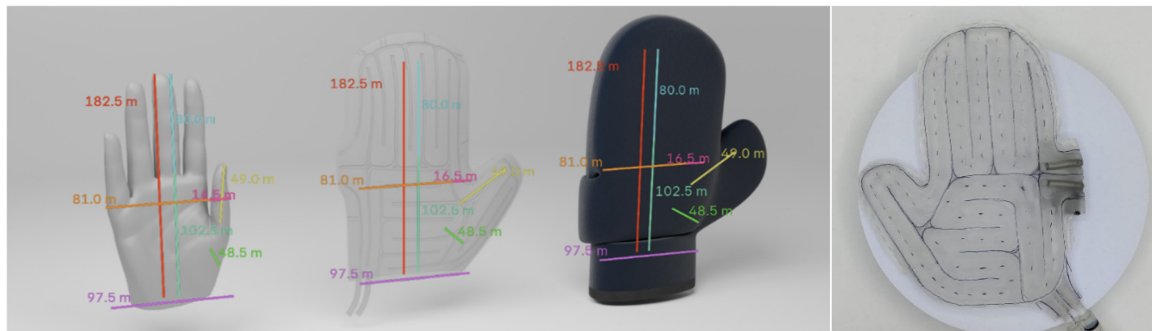


Figure 4. Parametric framework applied to hand scan, liquid bladder and mitten cover

4.1. Technical validation and verification testing

This study linked anatomically optimised designs to measurable cooling outcomes. Sensors on the hand tracked temperature changes, supported by data logging and thermal imaging to assess cooling magnitude and uniformity. Bladder designs were tested with a vapor-compression cooling unit under controlled conditions with iterative testing of design variations to identify the most effective configurations, ensuring improvements were quantitatively validated and clinically relevant. Achieving uniform and sufficient hand cooling remains a critical challenge in the design of a cryotherapy glove intended for the prevention CIPN. A common limitation of existing glove systems is that they rely on indirect cooling, offer inconsistent surface contact, or use a geometric design that fails to adequately cool the digits, a key consideration in design, given that CIPN symptoms typically emerge first and most intensely in the fingertips, and progress proximally in what is described as the “Dying Back” theory. By immersing the hand in 10 °C water, we can precisely provide full-surface contact with a thermally conductive medium that can serve as an idealised model of optimal heat extraction. The resulting temperature profiles can therefore act as a physiologically rounded reference for how the palm and individual digits should behave if a glove could deliver uninterrupted and evenly distributed cooling. This can form the foundation for a performance standard against which the glove designs can be evaluated. A series of controlled cooling experiments was conducted to quantify the amount of thermal energy released from the hand during prolonged cold exposure, to establish a standard cooling profile against which a uniform-cooling glove could be benchmarked. A total of 12 hand immersion trials were conducted across 8 participants, with participant 1 completing 5 repeated trials to assess intra-individual variability to characterise how the human hand releases thermal energy under ideal cooling conditions. Participants submerged their hand up to the wrist in an insulated container holding 1 litre of water at 10 °C, with miniature thermocouple temperature sensors placed on the palm, thumb, index and little finger to measure baseline temperatures recorded immediately before immersion and continuously monitored over a 60-minute cooling period.

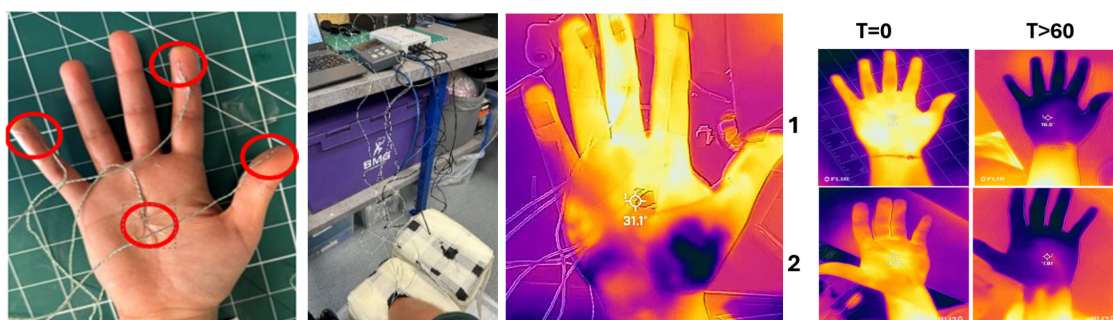


Figure 5. Thermocouples placed on centre of palm, tip of thumb, index and little finger (Left). Insulated with armaxflex material (mid right), optimised bladder thermal image (Right)

Heat extraction values, expressed as watts over the 1-hour cooling period, ranged broadly from 4.50 to 22.7 W, as seen in Table 2. Most participants clustered between 5-7W, with 2 individuals acting as high-output outliers, highlighting that some individuals can release significantly more heat than others. Heat extraction values for participant 1 alone ranged from 4.5 W to 10.5 W, with a mean of 6.93 W. When analysing according to vascular response, those who exhibited cold-induced vasodilation released significantly more energy during hand immersion at a mean of 12.48 W/h in comparison to those who demonstrated sustained vasoconstriction at a mean of 6.13 W/h. These values therefore reflect a thermoregulatory rebound mechanism, rather than typical conductive cooling alone. Furthermore, all digits can drop below 18 C within the first 5-6 minutes of submersion, rapidly approaching the temperature of the water. After this drop, the heat extraction dramatically slows as finger temperatures plateau, suggesting thermal equilibrium has been reached early.

Table 3. Comparative results of skin temperatures for limb-cooling

	Optimal contact (10C water bath)	PLCS Average (limb cooler)	Customised bladder (PD modified)	% improvement
Palm	17.98	31.92	22.7	24.7
Thumb	16.38	32.57	30.9	22.5
Index	16.32	30.77	21.2	24.2
Pinky	16.28	28.03	25	21

5. Discussion

The extensive literature review conducted at the outset of this study played a critical role in shaping the development of the customisable parametric framework revealing a clear set of parameters essential for effective personalisation. Identifying these parameters early enabled the creation of a systematic, rule-based design approach that could dynamically adapt to the diverse anatomical needs of individual users. This foundational framework supported an iterative, in-house prototyping phase in which multiple bladder and wrap variants were rapidly developed and tested. Early prototypes allowed refinements in channel layout and material thickness, progressively resolving issues such as fit irregularities or thermal inconsistencies. Through this iterative cycle, the team achieved the ability to manufacture user-specific bladders suitable for controlled evaluation. Progression from concept to functional prototypes was essential to enable the structured three-phase validation protocol used in this study, ultimately improving both the accuracy of data collection and the fidelity of performance comparisons across design iterations. Using a best-case test rig and the predicate cooling device, enabled a clear comparison between baseline and potential performance against the parametrically optimised designs. In phase 1, the water-submersion benchmark established the theoretical maximum heat extraction achievable from the hand under idealised conditions. Temperature sensors placed across multiple anatomical sites recorded consistent reductions in skin temperature over the 30-minute period, providing a robust reference against which subsequent device performance could be compared. Agitation of the water ensured uniform heat transfer and eliminated localised thermal gradients, strengthening the reliability of the baseline measurements. This phase confirmed the potential range of energy extraction and highlighted the upper limits that any wearable device could approach under optimal contact conditions. Evaluation of the existing hand-wearable cooling device with circulating liquid bladders.

The comparative data showed measurable reductions in skin temperature, demonstrating the device's functional ability to extract heat; however, differences between this phase and the idealised baseline indicated areas of imperfect thermal contact and fluid dynamic inefficiency. Sensor data across individual digits, the palm, and the dorsum of the hand highlighted specific zones where contact was suboptimal, and where heat extraction could be improved. These findings underscore the importance of anatomical conformity in determining cooling efficacy and provide actionable feedback for iterative design improvements. Incorporating PD optimisation, demonstrated the value of bespoke geometric adaptation in improving both fit and thermal performance. By integrating individual hand measurements into the parametric framework, optimised bladder geometries were generated, with preliminary results indicated that the optimised devices approached closer to the baseline energy extraction values, with an average improved heat extraction of 23.1%, suggesting a more uniform contact across monitored sites.

The absence of comparative studies across multiple CAD platforms means that the current results represent a proof-of-concept rather than a fully validated design methodology. Further work should extend the framework into other CAD environments such as Rhino/Grasshopper or Fusion 360 to assess interoperability, workflow efficiency, and scalability to diverse wearable medical applications. Parametric modelling and thermal simulation in CAD packages could be considered in the future such as FEA simulations or other tools for accurate repeat reporting on heat transfer analysis as a parallel to physical data collection. Future research could also incorporate the production of commercially refined prototypes and the implementation of iterative testing cycles with further users. These approaches require additional resources, including tooling and manufacturing infrastructure and material procurement. By conducting the initial development stages predominantly in a digital environment and utilising in-house prototyping facilities, we have mitigated costs, reduced time investment, and avoided the logistical demands of physical prototyping. Nonetheless, transitioning into practical trials with patient participation will be essential for translating the proposed framework to be clinically effective.

6. Conclusion

These findings extend beyond practical prototyping to offer a measurable scientific contribution to knowledge in wearable thermoregulatory design. The results demonstrate that geometric personalisation is not merely an ergonomic refinement but a thermodynamically significant variable: parametric adaptation of fit produced an average improvement of >23% in heat extraction under controlled conditions. This establishes a quantifiable relationship between anatomical conformity and thermal transfer efficiency, advancing understanding of how contact uniformity, surface coverage, and fluid pathway distribution influence conductive cooling performance. The study therefore contributes a validated parametric framework linking anthropometric modelling to measurable thermal outcomes. By embedding anatomical variability directly into the design, the research reframes fit as a performance-critical parameter rather than a secondary comfort consideration. The structured comparative methodology further provides a repeatable evaluation model for early-stage medical device optimisation, enabling systematic benchmarking against predicate devices and simulated baselines.

While the work remains at the feasibility stage and does not constitute clinical evidence, the findings provide empirical support for personalised geometric adaptation as a performance-enhancing principle in wearable cryotherapy systems. Further research involving larger and more diverse cohorts, long-term durability testing, and detailed energy extraction quantification will be required for clinical validation. The successful application of this methodology to limb cooling demonstrates its transferability across anatomical regions, underscoring the robustness of the theoretical framework and its potential to inform broader developments in personalised wearable medical devices.

Acknowledgement

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