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Human-centred engineering design: a cross-disciplinary product innovation practice

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Abstract

This article introduces a Human-centred Engineering Design (HcED) practice, which values human aspects. This practice engages deeply into (1) human geometry and motion for specific tasks, (2) product and manufacturing complexities through rapid prototyping, and (3) the broader human task context. This cross-disciplinary method combines ergonomics, AM, sensor applications, and multiple design practices. The framework provides concrete tasks to drive innovative designs in engineering. The study, grounded in design research case studies, led to five new Paralympic Rowing world records.

Keywords: human-centred design, engineering design, data-driven design, product design

1. Introduction

Designing specialised products for differences in human needs and anatomy requires various perspectives and integration of design practices. Design practises needs to evolve with new technologies. With a cross-disciplinary mindset, the designer needs to consider the fundamentals in various fields such as Systems Engineering, Additive Manufacturing (AM), Ergonomics, Phycology, Social science, movement science, sports performance and more. However, each design practice enacts its biased productive thinking, such as requirements and technology in engineering design, aesthetics and form in industrial design, or needs and new experiences in human-centred design. Engineering design, including AM and sensor technologies, offers rapid prototyping techniques and in-situ evaluation (Berg et al., 2023; Sletten et al., 2021). Industrial Design expertise develops forms that delight people in their lives (Krippendorff, 1989). Similarly, Human-centred Design practices explore the physiological and psychological, such as needs, perception, behaviour, and experience in, e.g., human-product interaction. However, Design Innovation requires the integration of these different practices. This article outlines a framework integrating the practices of manufacturing, form-giving, and human performance. We illustrate this integrated practice through an example of a product design for Paralympic Rowing, resulting in increased training capabilities and five new World Records. Assisted by new product design, human performance increased from 10:13.63 to 9:47.83, 25.8 seconds faster. The framework provides various design activities that can be incorporated into any human-component interaction design. An essential part of the integrated practice involves leveraging recent technological advancements, allowing handling added complexity and functionality (Birkelid et al., 2022; Bjørken et al., 2022; Gibson et al., 2021). Recent advances in AM technologies and procedures enable designers to prototype rapidly where they previously were restricted by manufacturing capabilities (Gibson et al., 2021). Fused Filament Fabrication (FFF) provides many design possibilities, demonstrated in the outlined case study. AM significantly reduces production time of specialised, low-quantity components. These new developments enable designers to rapidly explore design aspects, including the experience and performance of human-product interactions, material testing, and product forms. Designers now have the ability to create vast numbers of prototypes. This not only enables but also demands a new mindset, integrating different perspectives and design practices. This integrated practice aims to innovate designs by combining approaches. This includes data-driven design enabled by sensor technology, AM-enabled iterative and rapid prototyping, and human-centred design to explore human experience and performance. The outlined HcED framework is based on the integrated design practices illustrated trough Paralympic rowing case study (Eikevåg et al., 2020, 2022; Severin et al., 2021).

2. Background

Creating innovative products addressing complex challenges requires integrating diverse disciplinary perspectives into comprehensive design practices (Archer, 1964; Auernhammer and Roth, 2023; Fuller, 1957; Moholy-Nagy, 1947). A main challenge is integrating diverse design practices that utilize new technological developments.

2.1. Engineering design: Opportunities of additive manufacturing

Designers work to create innovative solutions using various techniques. However, traditional production methods inherently limit the creation of complex designs. In product development, completing a single iteration cycle can be both time-consuming and costly. However, for the exploration and development of valuable products, rapid and cost-effective prototype iterations are crucial. 3D printers have become more robust and reliable over the past few years, and sales have increased exponentially since 2012 (Campbell et al., 2018). In 2022, 2.2 million 3D printers were sold, and within 2033, it is expected to reach 25 million printers sold each year ("3D Printing Market," 2023). FFF provides new opportunities due to low hardware costs and rapid production capabilities. Two main material categories are available for FFF: Consumer-grade (low-performance polymers) and high-performance materials. Because consumer-grade materials e.g., PLA, have reduced mechanical properties in cyclic loading applications (Morettini et al., 2022), they are unsuitable for end-use component production due to low fatigue resistance. However, they are suitable for iterative prototyping, where sustaining loads is necessary but the demands are less rigorous (Eikevåg, 2023a). The affordability of consumer-grade materials like PLA has effectively removed material cost constraints from the design process. Using these polymers, FFF can achieve deposition rates up to 500 g/hour, removing wait-time limitations. Modern FFF 3D printers offer a scalable AM method in terms of product size, and costs starts at 300 USD. The FFF process has few geometric restrictions and is continuously evolving. It is possible to 3D-scan the human-product interface, transfer it to components, and perform generative design or topology optimisation, resulting in unique individualised products. Designers are empowered in their iterative prototyping activities, removing design restrictions such as hiring manufacturers. They can conceptualise in CAD, manufacture large products or components, and test them with human users, all within a matter of hours. Recently, new hardware developments (Birkelid et al., 2022) enable (re)production of the final design using high-performance materials (Das et al., 2020), capable of sustaining fatigue loads using FFF. AM technology allows rapid prototyping to test, redesign, customise, and manufacture end-use components in collaboration with users to design truly innovative products. AM has the potential to enable rapid practices and a new mindset among designers to create innovative designs that were not possible a few years ago. Therefore, AM changes the way designers develop prototypes iteratively.

2.2. Human-centered Design: Design is the response to human needs

Designers explore the socio-cultural, artificial, and natural environment of people to identify needs and respond with a valuable and meaningful design (Arnold, 1959; Krippendorff, 2005; McKim, 1959). This human-centered design practice requires designers to develop design qualities, such as need sensitivities, productive and visual thinking, collaborative abilities, and mastering various techniques to engage and communicate with diverse people (Auernhammer and Roth, 2022, 2021). Need sensitivity allows designers to perceive situations and informs new directions to explore interesting and valuable concepts.

Rapid prototyping techniques, such as AM, enable designers to communicate a design concept and allow people to interact and experience the concept. These experiences and insights provide new, interesting directions for innovative design concepts, following productive thinking of re-centring and insight learning (Wertheimer and Wertheimer, 1959). To respond to the various interrelated tasks, a cross-disciplinary design practice is required to ground productive thinking in design practices to produce innovative products.

2.3. Integration of diverse design practices

Numerous scholars emphasized integrating various design practices (Archer, 1964; Auernhammer and Roth, 2023; Fuller, 1957; Moholy-Nagy, 1947). For example, need-finding, ergonomics, manufacturing (e.g., AM), and using new technologies (e.g., sensor technologies) allow designers to respond flexibly to various complex interdependent tasks. Rapid prototyping allows creating structural components, new product forms, communicating design concepts, and evaluating human-product interactions, to explore new design directions (Gibson et al., 2021). It also allows testing of various technological aspects, including fatigue and kinematic performance (Berg et al., 2023; Eikevåg et al., 2022). Such past design research suggests that integrating these diverse design practices drives creation of innovative products. Therefore, this article outlines a framework integrating diverse design practices based on investigating activities and practices within the case study of new product innovation in Paralympics rowing.

3. Methodology

This is case study research. An in-depth case was used to develop the framework. Interviews, documents, photos, videos, and sensor data were collected to examine the various disciplinary activities and practices. Collected data were analysed following three main steps. First, we identify specific disciplinary activities and practices, such as physical prototyping, athlete engagement, tool building to enhance parts making, tool building to measure performance, and material fatigue testing. Second, these activities and practices were analysed through a time-order matrix (Miles and Huberman, 1994). Third, activities and practices were categorized and abstracted into specific themes and phases, see Figure 1.

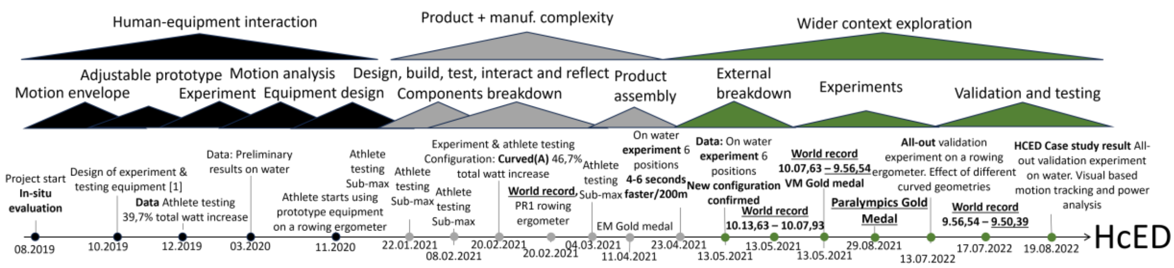

Figure 1. Data analysis: Framework development from the Paralympic rowing case-study

4. Framework: Human-centred Engineering Design (HcED)

The HcED framework integrates disciplinary practices enabled by new technology. In traditional manufacturing, a high level of product complexity relied on handcraft, limited by the skills of the crafter. Integrating AM and cost-efficient FFF with various design and manufacturing practices into a cross-disciplinary approach enables a high level of product complexity. Integrating sensor technology with human-centred design practices enables designers to create experiments that measure various human-product interactions. Open-source sensor systems capable of reading dynamic motions are rapidly developing (Johnston et al., 2022). These developments provide new opportunities, enabling integrating various design practices to re-think the design of existing products. To seize the opportunities emerging from these developments, it is essential to go beyond the current mindset and practice in engineering design towards a cross-disciplinary practice. This cross-disciplinary design practice for Design Innovation is illustrated in the HcED framework (Figure 2). The framework outlines the integrated practice enabling design of complex products to augment people's capabilities for high performance (e.g., Paralympic rowing). The HcED framework follows 3 specific phases, but as design requires

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refinement based on learning, phases can, and most likely will, be re-iterated based on insights gained later in the process (Beitz et al., 1996).

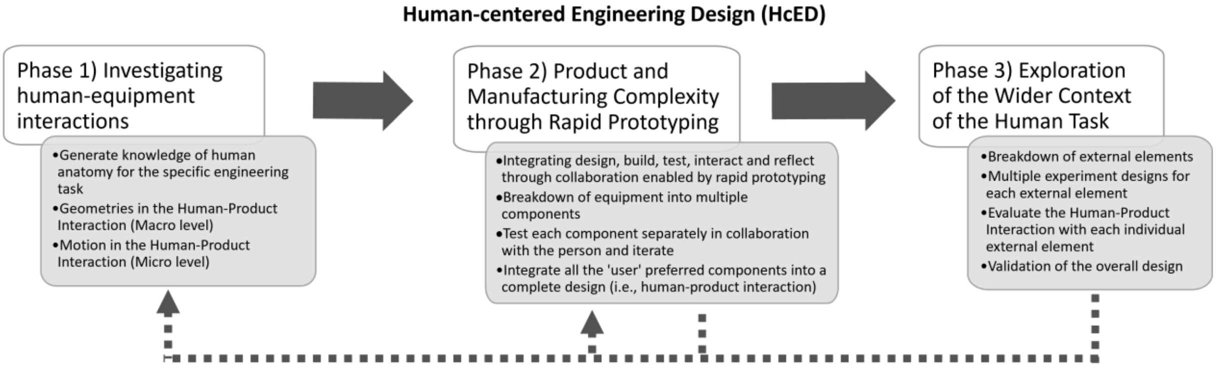

Figure 2. Human-centred Engineering Design framework (HcED)

The mindset underpinning the cross-disciplinary practice is overcoming limits and constraints through rapidly producing complex components. HcED requires designers to integrate different disciplinary practices and perspectives when using Design for AM (DfAM), sensor applications, and experiment design. This cross-disciplinary practice allows designers to complete the diverse aspects necessary for the full product development cycle (Auernhammer and Roth, 2023).

4.1. Phase 1) fundamentals: Investigating human-equipment interactions

The fundamentals are concerned with mapping configurations and capturing product interaction, both static and dynamic, with a focus on the specific challenge, such as efficiency, comfort, performance, and multi-functionality. By breaking product interactions into a macro level (static) and micro level (dynamic), we can design for fundamental requirements and added complexity. This breakdown focuses on the human aspects (e.g., physiology) of the specific task. In the fundamentals, this human-centred design approach centres around people, avoiding focusing solely on the artefact itself.

4.1.1. Geometries in the human-product interaction (macro level)

When designing a genuinely innovative product, it is essential to start at the most fundamental level. The HcED framework includes exploring geometries in human-product interaction by the following principles:

- Breakdown of the specific human task (into geometry)
- Build an adjustable prototype for the specific human task
- Design of an experiment to capture quantitative and qualitative data

The activities provide a complete map of the geometry of the human-product interaction for individual participants.

The **breakdown of the human task** is the first design principle, which identifies the basic geometries (Dreyfuss, 1959). The first principle of design is to identify essential human aspects, such as the flexibility of the human body, to determine the basic geometries of the specific human task. This principle focuses on the person and, e.g., how the human body can adjust and operate in certain situations and not on the product form or structure for the specific task. The human body has natural movement restrictions based on individual flexibility and anatomy. While movement restrictions and patterns are highly individual, some general movement restrictions and movement patterns can be identified across a larger population. When designing a product for people, it is important to avoid focusing on various product aspects, such as visual appearance or optimal structure, too early. For example, when designing a chair for a specific task, such as working on a laptop, we focus on identifying how many ways the human body can bend or be positioned to create a valuable experience, and not on the chair itself. The focus is on the person instead of reinterpreting existing physical products. Basic geometries can be determined either on an individual level for specialised products, or on a general level representative of the larger population.

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Build an adjustable prototype: To create a map of the human-product interactions, a physical adjustable prototype is required to perform an experiment. The adjustable prototype should at least include the full geometric envelope of the human body for the specific task. The prototype should also exceed this threshold to explore limitations. The prototype's only function is to enable experiments, and it should be created as rapidly with adjustability as the main characteristic. A wood mock-up created with hand tools is often the fastest solution (Eikevåg et al., 2020).

Design of an experiment: An experiment is required to determine the basic geometries of human-product interaction. Human-to-equipment interactions can both be dynamic and static. Independent of the type of product, an experiment with a measurable dependent variable representing the product aim (e.g., performance for sports equipment, comfortableness for chair), guides the exploration of the initial motions in the human-product interaction. The experiment aims to evaluate variations of basic geometries to identify individual customisation of the motion envelope provided by the product. We argue that human aspects, such as basic geometries, build a foundation providing direction in the design project on a "macro" level. The identified design constraints (e.g., motion envelope) provide the fundamentals for further design exploration.

4.1.2. Motion in the human-product interaction (micro level)

The micro level, i.e., the dynamic motion, should also be captured when conducting the experiment with the adjustable prototype. Capturing motions in human-product interactions allows exploring the different geometries (macro level) in the dynamic interaction. The principles providing micro insights for new product designs are:

- Using new technologies (e.g., motion tracking, IMUs, and load cells) in the experiment to capture the dynamic motion
- Analysis of geometry for implementing dynamic motion in future product design

Using new technologies: Advanced technology capturing data in experiments enables designers to explore additional complexity in addition to the basic geometries. State-of-the-art sensor systems can create insights previously unobtainable. The selection of sensors varies according to each specific design case. Newer technological developments may aid in the design project. For example, motion capture is a known procedure to capture movements, aiding design of equipment (Severin et al., 2021). The development of motion caption systems from reflector-based to video-based enables designers to perform in-situ experiments outside laboratory environments (Johnston et al., 2022).

Analysis of geometry: Gaining insight into human-product interactions in a dynamic setting enable designers to understand all of the different interactions. The technology-enabled experiment identifies outliers, providing an understanding of complex motions that can be translated into the product design.

4.2. Phase 2) rapid prototyping: Product and manufacturing complexity

Designers can create new complex product designs by understanding the fundamentals, such as human anatomy for the specific task, and data on dynamic interactions. There are many additional factors to consider in product interactions, e.g., how humans fit, perform, and feel. Rapid prototyping is all about learning. Designers can collaborate to iterate on the product design with individual users. This collaboration incorporates a design, build, test, interact, and reflect cycle, which generates new insights. The user can experience the design and give feedback on e.g. feel, comfort, and support. Designers can translate this feedback into a CAD model and produce new prototypes rapidly using FFF. One iteration cycle can take hours, as FFF enables a vast amount of prototypes with major design changes with little effort and low cost. The following principles are part of rapid prototyping:

- Integrating design, build, test, interact, and reflect through collaboration
- Breakdown of equipment into multiple components
- Test each component separately in collaboration with the user and iterate
- Integrate all user preferred components into a complete design (i.e., human-product interaction)

Design, build, test, interact and reflect: The product design we start with is based on the fundamentals of human-product interactions. A new design is created in CAD by parameter-based design, allowing rapid and easy modifications to a digital model. The product is then manufactured by FFF in a consumer-

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grade polymer (the material can be recycled afterwards). Then, the product is tested together with the user, providing valuable experiences, feedback, and insights. The interaction between the user and the designed product will assist the designer in the next iteration.

Components breakdown: In many cases several elements in combination constitute the product. In complex cases, if possible, a breakdown of the product into separate functions allows easier testing, more detailed user feedback, and precise measurements. For example, for a chair we can separate the fitment of the backrest, seat, armrest, and neck support. All these elements can be tested separately while maintaining geometries from the initial phase, such as backrest angle, seat angle, and chair height.

Test each component separately: After breaking the product into smaller components, we can test those components individually with the user. This aims to increase the quality of the final product. The user can then give feedback on specific product components, which makes it easier for the designer to implement feedback.

Integration into a complete design: Designers can integrate all product components into a final design after individual testing, and a complete fit for the specific task has been determined. The final design incorporates the complexity of the whole human-product interaction. The final design can then be manufactured by FFF using a high-performance polymer capable of sustaining fatigue.

4.3. Phase 3) exploration: Wider context of the human task

Designers still lack understanding of how the product interacts with other products after producing a full human interface by FFF because there are other environmental factors that influence the human-product interaction. Designers need to investigate the environment and objects that interact with the human interaction and with the product. Here, designers zoom out to answer the question: What are the dynamic interactions the product might be used for? For example, when designing a chair, designers should explore the different use environments and their impact. They must identify the chair's limiting product characteristics to add functionality (e.g., wheels) and design for adjustable use cases. The principles guiding exploring changing contexts and thereby adjusting the product design for different uses and environments are:

- Breakdown of external elements
- Multiple experiment designs for each external element identified
- Use new technology to evaluate the Human-Product Interaction for each external element
- Validation of the overall design of the Human-Product Interaction with the total environment

Breakdown of external elements: Designers can create great experiences for a specific need by breaking down external product components into individual elements and changing them. This flexibility allows designers to make changes to accompany diverse uses and contexts.

Multiple experiment designs for each external element to identify their optimum designs: After breakdown of external elements into individual elements, designers can create multiple experiments that map out how to adapt the product within the environment. Individual experiments is required for each external component, aimed at evaluating and identifying the optimum design of this specific component. Designers can redesign the product for each experiment (i.e., for each external element). After the optimum design solution of each component has been identified individually, all individual solutions are brought together into the product's final design.

Validation of the design: The last principle focuses on evaluating the final design in its intended environment, i.e., an in-situ experiment. Conducting experiments in its intended use context enable crucial experiences, data collection, and user feedback on product use. Designers gain important insight on whether the designed product adds value and is different from different product versions and other existing products.

4.4. Summary of HcED Framework

The HcED framework integrates different design practices enabled by new technological developments. The aim of this cross-disciplinary design practice is to rapidly learn by incorporating different design thinking perspectives on people, technology, and environment, by utilising different disciplinary practices (e.g., physical prototyping), and examining human interactions and experiences.

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Technological advancements enable rapid prototyping to learn fast and generate knowledge. An essential mindset is: any new prototype is never final. There will always new and interesting directions to be discovered. Designers are to generate a first design direction by investigating basic geometries and analysing motions. These fundamentals add value to any product design that aims to support defined tasks or needs people have. In rapid prototyping, fast iterations is the most important factor to learn rapidly. The mindset: create hundreds of prototypes incorporating the various complexities to experience and evaluate the human-product interaction. The last principles in the framework shift our perspective from the human-product interface to the external environment, to design and evaluation of the product in its intended use context. Designers are able to reinvent products through HcED, as exemplified in the following case study.

5. HcED case study: Paralympic rowing

The HcED framework is based on a case study of product design for human performance in Paralympic rowing. This case study illustrates how the principles in our cross-disciplinary design practice resulted in Design Innovation. The project ran from 2019 to 2022, and included over 200 physical prototypes.

5.1. Phase 1) fundamentals: Experiment design

At the macro level, breaking down rowing into basic geometries resulted in two basic geometries a) the back and its movements and b) the legs and its movements. To map out the human-product interactions of the basic geometries, our first laboratory experiment involved adjusting the angle of the backrest and legs with an adjustable wood mock-up (Eikevåg et al., 2020). By adjusting these angles (and thus the movement envelope), the athlete's power output increased from 126 W to 165 W (Severin et al., 2021). At the micro level, we gathered sensor data (power output, IMU, motion capture, load cells, ECG, etc.), and athlete feedback (interviews and questionnaires). We learned that while the Paralympic athlete felt subjectively limited by their impairment at 15° backrest, the quantitative data clearly showed that performance (power output) was greater at 25° backrest. We saw the conflicting data as an opportunity to explore new design possibilities.

5.2. Phase 2) rapid prototyping: Manufacturing over 200 prototypes

From phase 1 we had insight into the optimal motion envelope (by analysing quantitative sensor data) and athlete feedback (qualitative data). Based on this, we hypothesised that supporting the impaired region (at 15° backrest) while increasing stroke length (through a backrest with increased inclination) would produce additional power increases, resulting in a new design, a curved backrest with differentiating inclinations, as illustrated in Figure 3.

Figure 3. A) Design insights from HcED phase 1; B-C) Final prototype (Eikevåg, 2023b)

The curved backrest design underwent a series of design, build, test, interact, and reflect iteration cycles. Access to top-level athletes was limited, as they had limited time to participate in experiments. Long production times would thus prevent iterative prototyping. By using FFF and cost-efficient PLA, lead times were reduced to 5 hours (or less) per prototype, which allowed considerably more iterations and learning than conventional production methods would have. The rapid prototyping phase that followed explored various design solutions, all aiming to increase performance and human-product fit. We iteratively created all prototypes with FFF, where every iteration was tested with the athlete through a design, build, test, interact, and reflect cycle, while maintaining the identified optimal motion envelope (from phase 1). Figure 4 exemplifies a selection of different seatback designs, all of which were rapidly

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prototyped and user-tested. We also tested individual components that aimed to improve injury prevention. The resulting design yielded far superior performance, fitment, and injury prevention.

Figure 4. A selection of different design, build, test, interact and reflect cycles

The final design, the FFF-printed PR1 rowing equipment in Figure 3C, resulted in a power increase of 47,6%, from 126 W to 186 W, whilst optimising the human-product interaction within the identified optimal motion envelope. Two days after the final experiment, the redesign yielded a new world record in the indoor rowing world championship with the time: 8:18.5—13 seconds faster than the old record of 8:31.5 (Eikevåg et al., 2022).

5.3. Phase 3) Wider context: Adapting the environment

The final product design and the human-product interaction was determined in the previous phase. Now, we must explore the final design in its actual use context—rowing on water—and investigate the external elements (or products) interacting with the product. In the case of rowing, it is obvious what dynamic interactions the product might be used for. In Paralympic PR1 rowing, oars are the external elements interacting with the product and the human-product interaction: this extension of the human body transfer produced power to propulsion and is fixed by rowlocks (Figure 5D-E). With a set product design, we explored possible redesigns of oars and rowlocks in an experiment because it has the potential to further increase athlete performance, and validate the final design in its intended use context.

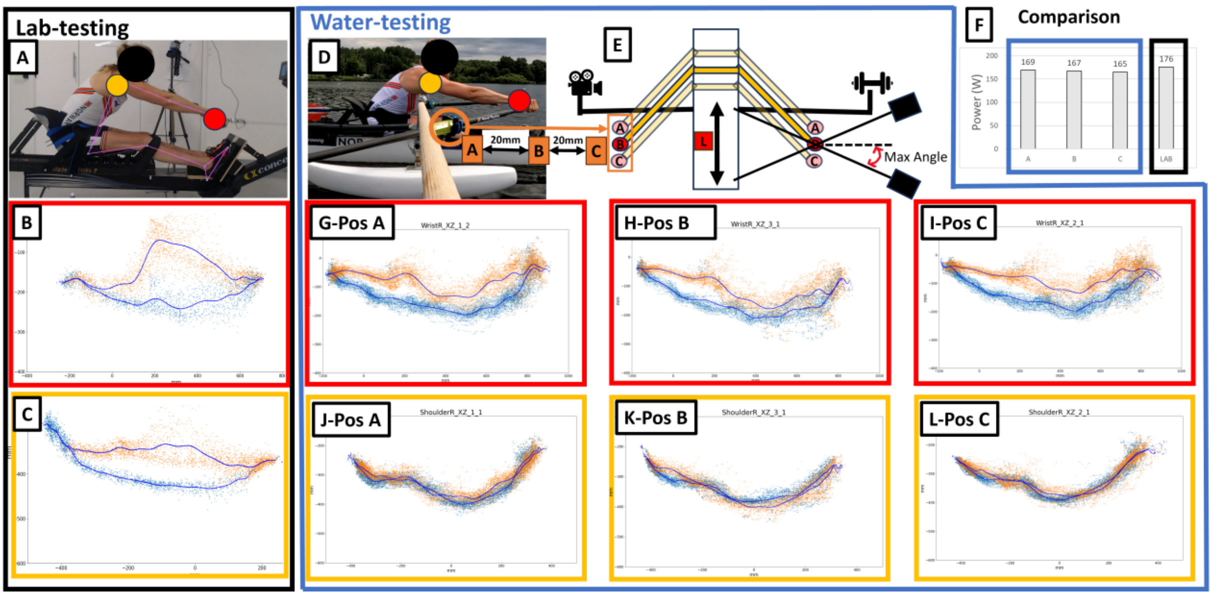

Figure 5. A) Laboratory experiment, shoulder (orange) and wrist (red). B) Wrist motion laboratory. C) Shoulder motion laboratory. D-E) In-situ shoulder (orange) and wrist (red) and Experiment setup. F) Power comparison G-I) Wrist movement of rowlock position A-C. J-L) Shoulder movement of rowlock position A-C

The in-situ—i.e., on water—experiment compared three rowlock positions, and collected data from multiple sensors, including motion capture (Johnston et al., 2022). Previous baseline experiments had been performed both in lab and on-water, allowing us to compare lab and in-situ motion envelope and performance (produced power). The in-situ experiment revealed that adjusting rowlock positions (Figure 5D) affects produced power. Rowlock position A produced 169 W, B 167.4 W (only 1.6 W less than A), and C 165 W. The difference between max in-situ produced power (169 W) and the max

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baseline produced power in lab (176 W), is only 7 W. This is a remarkable improvement when considering the original baseline produced power was 126 W (from the first experiment described in 4.1). By adjusting the on-water motion envelope through rowlock position we are able to harvest an additional 4 W, which in Paralympic PR1 rowing could constitute the difference between 1st and 3rd place. This highlights how important it is to identify, experiment, and iterate upon the design of the external elements interacting with the product. It is important to finetune the external elements, adjusting them to the new optimal movement envelope (which was identified in the previous phase). The motion envelope of both shoulder and wrists differs when comparing lab and in-situ, which is natural, because the rowlocks restrict motion in-situ, while there are no movement-restrictions in lab on a rowing ergometer. The back-forth (blue-orange in Figure 5) shoulder movement is similar in all row-lock positions on-water, but position A, B and C have different motion envelopes. We observe similar trends for wrist movements. Position B is arguably most similar to lab (i.e., unrestricted) shoulder movement. For wrist movements position C resembles lab most, but position B is not very different. Because B resembled lab motion envelope (i.e., completely unrestricted movement/how the body moves when there are no restrictions) most, and produced power was only 1.6 W lower than A, we recommended B as the final setting to the athlete. This fully utilises the newly discovered power increase through final product design and design of external elements, and shows the importance of validating the final design in-situ and simultaneously consider the wider context of the product task and what it interacts with. Lab and in-situ are inherently different, and both must be investigated. The results show similar power generation by the athlete in-situ as in laboratory settings, closing the project.

5.4. Impact and conclusion

The athlete has achieved 5 world records in 2000 m Paralympic PR1 rowing, all while using our equipment design. The new curved seat design has been adopted by every professional PR1 rower (although it should have been adjusted individually). The new product design changed the technique and motion envelope in Paralympic rowing. The time difference between first and last place decreased from 2 minutes during Paralympics in Tokyo 2021 ("Tokyo Paralympics," 2021) to 26 seconds in the World Cup in 2022 ("Poznan World Rowing Cup," 2022).

This article presented a cross-disciplinary human-centred engineering (HcED) framework. HcED outlines practical human-centred design principles and how to systematically apply them in a technology-enabled cross-disciplinary design practice. This design practice can produce true value for people (i.e., end-user) by designing innovative products. HcED was developed based on a case-study of Paralympic PR1 rowing equipment and has had international impact. The final product design, developed through HcED, has contributed our athlete obtaining 5 world records, a 47.6% power increase, and has been adopted by the world elite in Paralympic rowing.

Acknowledgement

The studies were approved ethically according to NSD-514085, and the athlete provided written informed consent prior to all studies.

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