STUDY OF EFFECT OF PERSONAL FLOTATION DEVICE ON PERFORMANCE OF ROWERS

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Arts

by

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August 2017

ABSTRACT

This study investigated the factors affecting the wearing of PFDs on rowing athletes' motion and performance. Pre-experiment tests were conducted with 7 elite collegiate rowers. Both quantitative and qualitative data from the pre-test indicated that conventional Type II PFDs have significant restrictions especially in the shoulder and hip joints and were considered along with the prevailing culture of PFD nonuse by rowers. Accompanied with multi-disciplinary knowledge, a new prototype was successfully developed to minimize these restrictions, to improve mobility, comfort, and effectiveness, which was proved by post-development testing with 6 out of 7 rowers from the initial test. Possibilities for further improvements on the prototype have been proposed and preliminary flotation test was conducted to confirm the adequate buoyancy. This study implied the importance of understanding body motion when designing for specific activity. Future studies with larger sample size, field test, and metabolism measurements are expected to provide more in-depth understanding.

BIOGRAPHICAL SKETCH

Manwen Li was born in Shijiazhuang, Hebei Province, China, in 1993. She grew up and attended school locally until moving away for Tianjin Polytechnic University to study Fashion design and Engineering. After graduating with top grades and honors, she started to pursue a master's degree in Apparel Design with great passion at Cornell University in fall of 2015.

From 2015 to 2017, while taking classes in different disciplines, she worked closely with her advisor, Professor Huiju Park. By dedicating herself to multiple nationally-funded research projects as a research assistant, she obtained the necessary skills and knowledge to start her own design research project. With Prof. Park's mentoring, she was able to contribute to several meaningful research projects and received opportunities to present projects both in HFES[1] and ITAA[2] 2017 conference. Finally, with the help of Prof. Park and her minor committee member, Professor Andy Ruina, she conducted a year-long independent research project and completed the final thesis in summer 2017.

[1] Human Factors and Ergonomics Society

[2] International Textile and Apparel Association

I dedicate this work to my parents, Jianzhong Li and Liqing Han

who have always fully supported me for whatever I pursued.

I also dedicate this to my little sister Manyao Li.

ACKNOWLEDGMENTS

I would like to give a special thanks to Professor Huiju Park for his full support and professional guidance on my research journey. I would also like to thank Professor Andy Lee Ruina for his valued opinions and expert feedback throughout my study.

Meanwhile, I obtained extensive knowledge about emergency rescue system, rowing safety, cold weather risks from Marc Messing, who also offered me lots of help on my thesis writing.

I appreciate the tremendously support by Cornell Rowing team, especially by the head coach Todd. P Kennett. I cannot accomplish the preliminary study and recruitment of human participants or even the whole project without his fully assistance.

I would like to thank all professors, staffs, graduate students in FSAD even for the trivial help they offered during my life here. Also, special thanks to Professor Susan P. Ashdown who led me to the world of 3D scan and anthropometric research.

Finally, I would also like to thank my dear friends Laura and Elliot for accompanying with me all my life in Cornell. And, my beloved friend Chi Zhang for supporting me along the journey.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

HCB	Half chest circumference on the back side
T	Traditional PFD
P	Prototype PFD

CHAPTER 1

INTRODUCTION

Water drowning is a significant public issue both in the United States and other countries around the world. The United States Coast Guard (USCG) official report (2015) showed that 626 people drowned in domestic recreational boat-related incidents in 2015. Although federal regulation requires that all boats must carry at least one life jacket for every passenger, less than 15% of drowning victims were known to wear a personal flotation device (PFD) (USCG, 2015).

Cold weather tends to increase the possibility of injury and fatality of on-water accidents. Body heat loss when immersed in cold water is about 25 times faster than when exposed to air at the same environment temperatures (Nielsen, 1978). Swimming, in harsh ambient conditions, becomes much more challenging compared to in warm conditions, which usually lead to rapid drowning. Additionally, cold water hastens the onset and development of hypothermia, which affects the body's vital organs such as heart, lungs, and brain. Even a moderate case of hypothermia abates a victim's physiological and psychological abilities, thus increases the risk of accidents (Mallet, 2002). Severe hypothermia may lead to even unconsciousness and post-rescue death. In the United States, approximately 600 fatal accidents happen each year because of hypothermia (National Center for Health Statistics, 2003).

According to International Life Saving Federation (ILS), without floatation devices, one usually drowns within minutes because of swimming failure when surrounded by cold water. Life jackets are designed to be worn to prevent submersion in advance when immersion occurs (ILS Drowning Report, 2007). In addition, PFD may lower the potential of drowning by 50% (Cummings et al., 2011). In inclement weather, wearing a life jacket can prevent the airway from being attacked by water and will, in most cases, prevent drowning (Golden and Rivers, 1975). A lifejacket also postpones the onset of hypothermia by diminishing the need for limb movement (Golden,1973). New York State law requires recreational boaters to not only carry but also wear life jackets between November and May for the aforementioned reasons.

Besides, cold shock and cold incapacitation are significant concerns to scholastic boaters since those symptoms could trigger drowning. It is expected that wearing PFD may improve rowers' body balance in water and opportunities to recover from cold shock or muscle cramp. Otherwise, boaters might be unable to move their body and make their heads out of the water, causing a life-threatening situation (Lockhart et al., 2005).

Despite high risks of drowning in cold water and considerable benefits of wearing PFD, however, rowers have been exempted from wearing PFDs since 1993. Although not wearing a life jacket is a common and traditional practice for rowers, accidents and fatalities still happen to rowers. Such incidents need to be paid more attention. For example, John Steve, 20, who was an experienced rower, died while coaching teenagers on the morning of June 25, 2004, on the Potomac River, VA (Black, 2007). Instead of focusing on their grief, his family made an effort to change the safety situation to other rowers. As a result, the crew club John was coaching agreed to revise their safety terms and USRowing, the national organization for the sport of rowing in the United States, agreed to release safety recommendations about life jackets usage in their next version of safety video. (Patterson, 2007).

Similar cases happened even victims were experienced boaters and skilled swimmers. Kevin Breckenmake, 58, a lifelong athlete and experienced rower, died because of capsizing and post-rescue failure on July 9th, 2015 while rowing in Gifford Pinchot State Park (Rago & Czech, 2015); furthermore, Michael Hill, a 48-year-old rowing coach, died of drowning without a life jacket on February 2nd, 2015 (Bergman, 2016); the most recent tragedy happened with Mohammed Ramzan, who was a 19 year old freshman rowing with Northwestern University's (club) crew team on April 10th, 2017 (Chiu, 2017).

All these cases demonstrate that even the most fit, experienced rowers or swimmers can become anxious when facing an accident, and various factors in on-water sports could lead to death. Certainly, the beginners, amateurs, single scullers and elder rowers could be more vulnerable. Quistburg et al. (2014) showed that boaters who consider themselves good swimmers are less likely to wear a personal flotation device, which largely increases the chance of suffering from unexpected accidents. The study also showed that boaters dislike life jackets partially because they are bulky and limit boaters' motion. Also, the materials used in life jackets tend to cause tactile discomfort such as chaffing injuries. Lack of either effective ventilation or thermal protection while wearing is another major limitation, which could increase thermal discomfort in wearing. As a result, engineering a more comfortable life jacket with improved fitting and mobility design will be paramount to encourage consistent use among rowers.

Previous studies present considerable knowledge and evidence of the potential risks among water-related sports as well as the needs and benefits of wearing PFD. Investigations of reasons and factors that affect PFD wearing habit from safety, sociological and psychological aspects also propose the needs of development of better-designed PFD (Quistburg et al., 2014; Cummings et al., 201; Stempski et al., 2013). In addition, influential factors in the improvement of rowing technique from biomechanical view are well established (Buckeridge, E. M. et al., 2014; Černe, T. et al., 2011).

Moreover, from the design perspective, some studies already started to explore methods to develop a better PFD. Lockhart et al. (2005) conducted a study and proved that PFD design that kept the head and upper chest out of water could lower down the core cooling speed and better preserve body heat and mental performance compare to the one that offers horizontal flotation. Kim et al. (2014) proposed ergonomic patterns with heterogeneous thickness for a well-fitting life jacket with improved mobility.

But there indeed has been research gap in the knowledge of the relationship between wearing PFD and performance of rowing. Scientific approaches that combine sports biomechanics and ergonomic principles are absent in PFD design trials. Traditional life jackets are produced with a primary emphasis on buoyancy, which entails the use of thick foam materials and rough design, resulting in disturbed mobility and poor comfort in active water sport like rowing. With an understanding of environmental challenges and human factors, such research gap can be filled with a technical design approach and engineering design thinking for a PFD with enhanced mobility and comfort.

Purpose of the Study

Based on the identified research gap, this study aims to develop a prototype of improved PFD specifically designed for the sports of rowing. The prototype is expected to fill the niche market where the negligence of rowing safety needs to be subverted.

Research objectives are to;

1) identify needs for improved mobility and overall comfort during rowing.

2) identify the impact of wearing traditional PFD on rowers' motion and performance.

3) design and develop new prototype PFDs with more unobtrusive appearance, improved comfort, and minimal impact on rower's performance, and

4) evaluate the effectiveness of the new prototype designs.

CHAPTER 2

LITERATURE REVIEW

"Designing better fitting and more comfortable life jackets could help increase life jacket use." (Quistberg et al., 2014) To achieve a better-engineered life jacket specifically for the sport of rowing, understanding the knowledge in related fields is necessary. This chapter serves as a review of the literature and existing knowledge as follows:

2.1 Drowning and boating safety facts

2.2 Cold water & hypothermia

2.3 Risk without PFD and factors affect PFD usage

2.4 Biomechanics of Rowing

Rowing Technique and Performance

2.5 Design Consideration

Mobility Consideration

Buoyancy Consideration

Thermal Comfort

2.1 Drowning and boating safety facts

Drowning is a common but preventable public safety issue, which is the 3rd primary cause of injury death worldwide. 7% of injury-related deaths can be attributed to drowning. (WHO, 2016). According to reports published by World Health Organization (WHO) from 2011-2016, there are approximately 372 000 annual deaths caused by drowning worldwide. However, WHO claimed that the amount of deaths might significantly be underestimated because of the limitation of data collection (WHO, 2016).

Every year, the U.S. Coast Guard reported thousands of accidents happened in water and approximately dozens of million dollars' damage as results of boating accidents. Among those victims, drowning is always the top reason that responsible for death – among the known reasons for death, 76% of them are because of drowning. (USCG, 2015). The cost of drowning accidents is also considerable. Coastal drowning itself within the United States costs approximately 273 million USD every year directly and indirectly. As for other countries around the world, the aggregated annual cost of drowning injury is 85.5 million USD for Australia and 173 million USD for Canada. (WHO, 2016)

Prevention is critical to avoid such tragedies and loss. According to USCG official report (2015), 85% of drowning victims did not wear a personal flotation device despite that federal regulation requires all recreational boats to prepare a life jacket for each passenger. In addition, the report shows that the remaining 15% of the fatal accidents (from 1984-1991) were not attributed to the failure of the PFD itself, but rather to misuse of PFDs, hypothermia, or a variety of other factors. Although some accidents will continue to occur regardless of warnings and regulations, a considerable number of drownings could have been avoided if more boaters wore PFDs at the first place (Treser et al., 1997).

Environment factors also play a critical role in water-related accidents. According to the USCG's official reports (2013-2015), type of body of water, water condition, wind, visibility, and water temperature are all the influential factors that affect accidents and death probability. Especially, water temperature is a critical factor for mortality rate. In 2015, the USCG's reports indicate that when water temperature below 50 °F, death rate (28.33%) is almost twice as when water temperature is above 50 °F (13.8%) (USCG, 2015). The higher fatal rate in inclement weather presents a compelling reason to encourage PFD use among boaters in such weather. The importance of wearing a life jacket in cold weather will be demonstrated in following sections in this chapter.

Besides, the age of boaters and number of persons on board are also influential factors. The report also states that boaters who are over 55 years old are more vulnerable to fatal accidents. Also, single-person boating shows the highest accident number and death rate among all the other multi-person boating.

Higher risks also exist among amateurs and beginners of water sports. When boating or participating in other water sports, inadequate knowledge about operating the watercraft or boat is a leading cause of accidents. Those that wish to participate in water sports and activities should have at least the basic knowledge of how to operate the equipment or boat that is being used (CDC, 2012).

Furthermore, types of sports also influence the accidents and death rate. As for rowing, in 2015, 209 Rowing/Paddling boats involved in on-water accidents, including 117 deaths. Compared to other types of vessels, rowing/paddling has the highest death rate, in which 88% of them died because of drowning (USCG,2015). In New York State, 2015 Recreational Boating Report indicates that 65% capsized accidents happened in rowing or paddling boats, which tend to be the most vulnerable vessel to capsizing (New York State Parks, 2015). The high capsizing and accident rate further identified the needs of PFD, particularly for this sport.

Understanding the significance of drowning issues and factors that would affect this problem is the base of my study. All the information from official reports and data above helped me find the direction of this research and the issues needed to be unraveled in this study.

2.2 Cold water & hypothermia

Cold water can increase the risk of death when accidents happen. The danger of cold water can be simply explained by its high thermal conductivity. Under immersion incidents, water's thermal conductivity is approximately 25 times faster compared to air. Consequently, heat loss may be about 25 times faster when immersed in cold water rather than when exposed to ground activities at equivalent environment temperatures (Nielsen, 1978). When the temperature of the water is below 50 °F, significant involuntary physiological responses occur, which may cause death more easily (Šrámek, 2000).

USCG's 2015 annual report specified the number of deaths and injuries in different water temperature (Table 1). The data indicate that total death and injury rate increased significantly when water temperature is below 50°F. Furthermore, the death rate is two times more in cold water comparing when water temperature is above 50 °F.

Table 1 Death and Injury rate of drowning in different water temperature

Water temperature	Below 50 °F	Above 50°F

Injury & Death rate	93.33%	75.95%
Death rate	28.33%	13.8%

Note: Original data from USCG, 2015, summarized by the author

For different ranges of water temperature, the estimated survival time posted on the United States Search and Rescue Task Force website (Table 2).

Table 2 Expected Survival Time in Cold Water

Water Temperature	Exhaustion / Unconsciousness in	Expected Survival Time
70–80° F (21–27° C)	3–12 hours	3 hours – indefinitely
60–70° F (16–21° C)	2–7 hours	2–40 hours
50–60° F (10–16° C)	1–2 hours	1–6 hours
40–50° F (4–10° C)	30–60 minutes	1–3 hours
32.5–40° F (0–4° C)	15–30 minutes	30–90 minutes
<32° F (<0° C)	Under 15 minutes	Under 15–45 minutes

Note: Reprinted from: Cold Water Survival. Retrieved February 27, 2017, http://www.ussartf.org/cold_water_survival.htm

Meanwhile, cold water would also lead to hyperthermia. In relative warm water temperatures of 21–24°C, physical activity (usually swimming) will impede the body cooling speed by generating heat through metabolism. Whereas in very cold water, activity speeds up the heat loss because of an higher peripheral blood flow and larger body surface contacts to cold water (Turk et al. 2010). A study done by Hayward et al. (1974) also confirmed that the thermogenic response was less efficient in the cold water, the mechanism cannot balance the heat loss of body when it is embraced by the cold fluid. Therefore, hypothermia can always happen in such condition. In immersion hypothermia, inhalation of water may contribute to a lethal outcome, while in moderate water temperatures, drowning may contribute to death rather than hypothermia (Tipton et al. 1999).

Noticeably, elderly people are more invulnerable to hypothermia, since they often have a aggregation of multiple risk factors, such as higher level of immobility and natural diseases. Results from a study conducted by Krag and Kountz suggest that the function of peripheral vasoconstriction triggered by hypothermia is impaired in elder age (Krag & Kountz, 1950).

The theories and facts presented above proved that cold water can impair the human body's physiological mechanism and increase the possibility of the fatality. Therefore, personal flotation devices are critical for the human body when water temperature is relatively low, especially for elderly people, beginners of rowing, and amateurs.

2.3 Risk without PFD and factors affect PFD usage

The term 'personal flotation device' (PFD) is generally understood as flotation devices such as lifejackets, as well as other types of buoyancy devices designed to keep the wearer afloat in the water.

The International Life Saving Federation formally endorsed the final recommendations of the World Congress on Drowning, which includes encouraging of life jacket wearing (ILS Drowning Report, 2007). WHO's global drowning report also claimed that drowning could be prevented by using PFD (WHO, 2016). Centers for Disease Control and Prevention (2012) concluded that failure to wear life jacket increases the risk of drowning.

To explore the correlation between wearing PFD and fatality rate of drowning among recreational boaters, Cummings, Mueller and Quan (2011) conducted the matched cohort study of data presented by USCG from 2000 to 2006. As the outcome, they estimated the risk rate for drowning fatality when comparing between boaters with and without a PFD. The analysis includes 878 drowning deaths happened with

1597 boaters in 625 vessels. The result indicates that wearing a PFD have the potential to avoid one death out of two drowning cases among recreational boaters.

Stempski et al. (2013) performed a case-control study by analyzing Washington Boat Accident Investigation Report Database from 2003 to 2010 with the case and control group corresponding to the fatally injured and non-fatally injured boat occupants. Among all the boaters in their study, fatalities were 2.6 times more unlikely to be wearing a PFD comparing to the survivors and 2.2 times more likely that their boats do not have any safety features. It demonstrated the point that increasing PFD use, adding safety features on the vessel are critical strategies to prevent fatalities in the future.

A review of recreational drowning interventions for adults from 1990 to 2012 was done by Leavy et al. (2015). They selected six studies for comparison and analysis to reinforce the need to address adult drowning prevention. This journal article also confirmed that use of PFD should be promoted to prevent death from drowning.

Bugeja et.al (2014) conducted a retrospective population-based study to investigate whether the mandatory regulation of PFD wearing in Victoria reduced drowning death since it came into effect. They compared the annual number of deaths for 6 years before the year of regulation executed (2005) and 5 years after it using Mann-Whitney U test. The analysis showed a significant reduction in drowning deaths among all recreational boaters ($U=30.0$, $p=0.01$) and among different kinds of strata that categorized by age, boat type, and activity. These findings provide additional support for the fact that the use of personal flotation device can lower the possibility of drowning among recreational boaters.

Studies that focus on behavioral factors indicate that the most common reasons for the non-use of life jackets are bulkiness, discomfort and the belief that it is only necessary for children and weak swimmers. In addition, Baker et al., (2009) and Lucas et al. (2012) showed that the belief that life jackets may be ineffective, or may be useless in severe weather also contributed to the nonuse of PFD. Moreover, Nguyen et al. (2002) found that people involved in different types of water activities have different perceptions of potential risks and prevention methods. It suggested that effective interventions must be developed not only for the general population but also for certain sub-population specifically, which would promote the adoption of safety behaviors during water activities.

Quistberg et al. (2013) conducted a qualitative study among regular boaters to explore influential points associated with life jacket use by different age groups of passengers. Four focus groups were executed with 16 boaters' participation. According to the data, most boaters reported inconsistency on their habit of using life jackets. Usually, they just wear it when environmental conditions were poor. Results indicate that substantial obstacles to constant life jacket use include discomfort and the confidence of sufficient swimming skills. However, the use of inflatable life jackets indeed improves their behavior. The study concluded that designing more comfortable, better-fitting life jacket with attractive appearance will be significant for encouraging consistent use.

Based on aforementioned studies and official data sets, it is confirmed that using PFD largely increases the chance of survival from drowning accidents, in particular for the sport that has high death rate but low PFD using rate - rowing. Bulkiness, discomfort, and poor design of PFD always prevent rowers from wearing them. It is concluded that designing more comfortable, better-fitting life jacket with an attractive appearance for rowers will be significant for encouraging consistent use, which will largely reduce fatalities.

2.4 Biomechanics of Rowing

Rowing is one of the oldest and most traditional competitive sports in the world, which can be traced back to Ancient Egyptian periods. It is the sport that requires athletes sit in the boat towards the direction opposite to its movement and propel the boat by pushing against water with oars. The goal of this sport is to propel the whole system (the rowers and the boat) pass through certain distance with the shortest time.

Two types of rowing are commonly recognized, namely sweep and sculling. Sweep rowers are with only one oar per person and propel on one side of the boat. They come in pairs of 2 to 8 people in one boat with or without a coxswain. As for sculling, every rower has two oars symmetrically locate on two sides of the boat, which can be performed by 1 to 4 athletes (FISA, 2002).

Although the procedures of sculling and sweep rowing is substantially identical, sculling is recommended for beginners because of its symmetry. Therefore, sculling technique were presented as instructional section of the FISA Coaching Development Program Course (FISA, 2002). Besides, most biomechanics and physiologists focused on sculling in their studies of rowing because of its features of symmetry and foundation.

Rowing is a cyclic activity that contains the following 4 stroke phases: catch, drive, finish (sometimes referred to as the release), and the recovery. Advanced rowing requires these phases repeated as accurately as possible for more than 200 cycles during the competition. Therefore, competent rowing requires good consistency from stroke to stroke (Smith & Loschner, 2002).

Table 3 Rowing motion anatomy

Phase	Demonstration	Description
Catch		Thighs and torso are compact while shins vertical towards the water; arms are fully extended when the oar get into the water.
Drive	 	Legs and back begin to extend backwards; then, arms begin to pull the oar for acceleration of blades through the water.

Finish		Hands come towards the abdomen, where the hands tap down to retract the blades out of the water. Blades are feathered to keep parallel to the water for minimum drag force from water. An angle of 110 degree between upper body and pelvic is considered to be optimal.
Recovery	 	The recovery operates with opposite sequence of the drive. The hands bring the oars to an extended position. Hip pivots to move upper body forward. Slide starts to move with hip when torso passes through 90 degrees. Finally come back to the beginning of catch.

Note: Figures from "Rowing Biomechanics: What constitutes optimal, efficient technique?", retrieved from: http://rowingbiomechanics.weebly.com/

Rowing Techniques and Performance

Dr. Nolte (1991) from FISA[3] Coaching Development Program Course also proposed 4 principles for ideal rowing technique, which are also common practice followed by coaches in the past decades:

> Principle Number 1
>
> All movements should be performed in a way that the rower is able to transfer his/her physiological performance into optimal propulsion.
>
> Principle Number 2
>
> A longer stroke is necessary to produce a higher level of rowing performance.
>
> Principle Number 3
>
> The movement of the rower should be as horizontal as possible so that the perpendicular displacement of the center of gravity is minimized without losing length in the stroke.
>
> Principle Number 4
>
> The relatively horizontal velocity of the rower to the boat should be minimum. Ex: The displacement of the center of gravity in the horizontal plane should be minimized without losing length in the stroke and there should be no lost time with stops or pauses. (Nolte, 1991, p. 87)

Regards to the biomechanical factors affecting rowing performance, scientists and researchers conducted many related studies.

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[3] The World Rowing Federation, FISA (from the French, Fédération Internationale des Sociétés d'Aviron) is the governing body of the sport of rowing. It is empowered by its 151 member National Rowing Federations, the National Olympic Committees and the International Olympic Committee to govern the sport of rowing.

Baudouin and Hawkins (2002) confirmed that the oar plays a critical role in the entire rower-shell system by transferring the energy produced by the rower's movement to the end of the oar. Kinematic moments generated by the rower's body cause relative movement to the shell, which also lead to an interrelated movement of the oar that is hindered by the interplay with the water. By prescribing an arc in the water, force is produced through the oar during the whole process of the rower's movement. This review concluded that changes in the movement pattern of the oar would have an influence on the entire system. Figure 1 is the oar positions in different phases of a stroke.

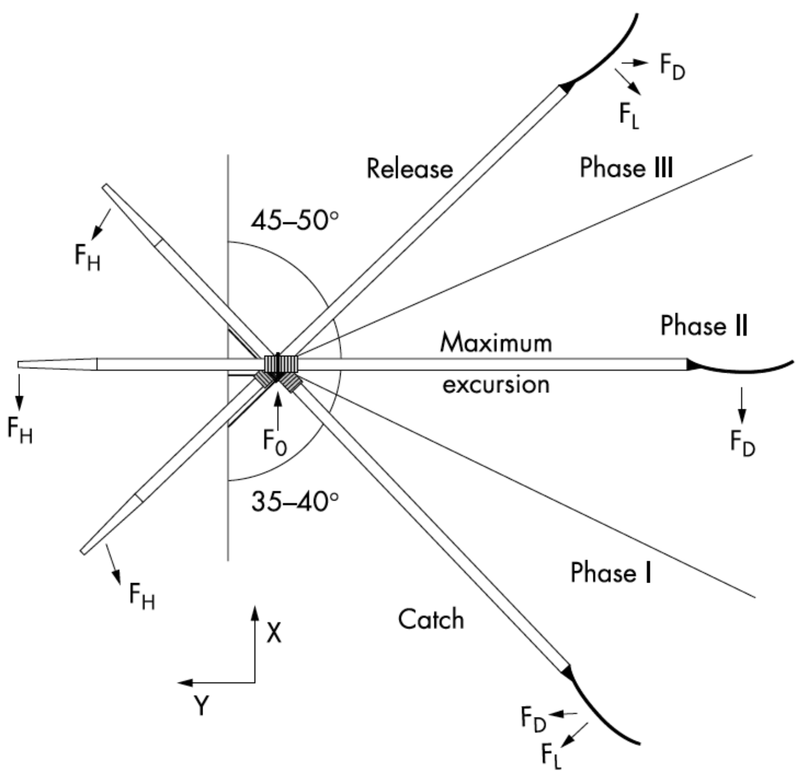


Figure 1 Oar positions in different phases of a stroke. (Baudouin, 2002)

By using a technique that can measure spinal and pelvic motion during rowing while measuring force generated at the handle, McGregor (2004) investigated ten collegiate male rowers with instrumented ergometer. It is observed that femoral flexion tends to increase with higher stroke ratings, meanwhile, power output increased significantly with relative stable stroke length. This study showed evidence of the importance of keeping an adequate range of movement to achieve better power output, especially for lumbopelvic flexion.

Cerne et al. (2011) indicated that there are notable distinctions of biomechanical parameters between the experts and beginners. One of them is that the strokes of the expert-level rowers were longer and more consistent in all rates. Non-experts, however, have shorter stroke length that increased with increasing stroke rate. In a word, to achieve better performance, relatively long and stable strokes are necessary for a rower. Comparison of trajectories presented in Figure 2.

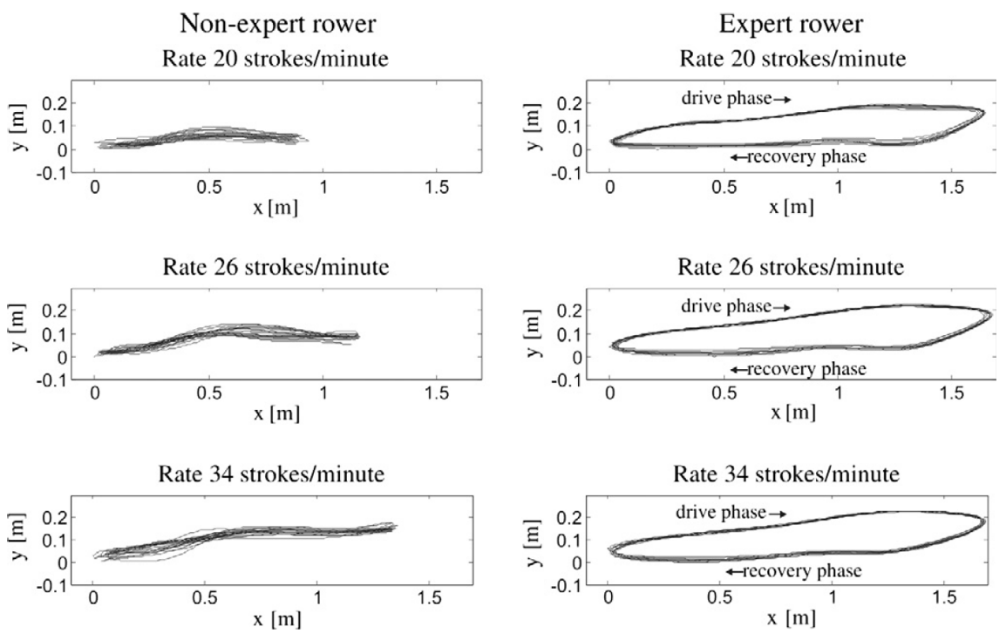


Figure 2 The handle motion trajectories of subjects presented in the sagittal plane (Cerne et al., 2011)

Buckeridge et al. (2015) showed that almost 35% of the variance in foot force while rowing is explained by hip dynamic. As a result, hip flexion, especially at catch position, is regarded as a key variable that influences foot force generation. This study provides solid evidence that even slight adjustments in rowing technique would have a notable impact on kinematic force, which could ultimately influence rowing performance and injury potential.

Hereto, basic biomechanical knowledge and principles of a good performance have been presented. Past literature confirmed following points with evidence:

1. Small changes in rowing motion will give rise to the influence on performance and injury risk.

2. Hands movement is critical since it will further affect the trajectory of oars which generate the force needed for the whole unit.
3. Long and stable stroke is preferred for better performance.
4. Adequate range of movement is important to achieve better power output, especially for lumbopelvic flexion.

2.5 Design Consideration

As mentioned earlier in this chapter, one of the most important reasons why traditional PFDs have not been widely used among boaters is because of their bulkiness, poor design and fitting (Quistburg et al., 2014; Baker et al., 2009; Lucas et al., 2012), which could be improved by a better engineered PFD. From this perspective, many designers and researchers who aim to develop a better PFD contributed their knowledge and ideas in multiple fields.

In this subsection, design consideration will be discussed in terms of mobility, buoyancy, and thermal comfort.

Mobility Consideration

To minimize the influence on wearer's mobility, there have been efforts to develop the PFD with a profile as minimum as possible by utilizing the inflatable installation. For example, William (U.S. Patent No. 5,954,556) invented the Emergency Flotation Device with the appearance of a belt that can be wear on the waist. Daniel (U.S. Patent No. US 8,920,205 B2) registered his patent of a small inflatable PFD that can be attached to multiple places on user's body, which looks just like a wristband or a watch.

However, research on the impact of PFD design on rowing motion is very rare. Kim et al. (2014) identified that life jackets currently available for water sports are still inadequate in terms of their fit to human body contour as well as the range of movement that they allow. To reduce the restriction generated by traditional PFD, they developed a contoured life jacket pattern in this study based on the three-dimensional shape of the human torso. Foam flotation material (Polyethylene foam) was applied in heterogeneous thicknesses in different sections on the torso to accomplish the required buoyancy and promote movement capability. But the developed life jacket is not specialized for certain sports or certain group of people, as a result, specific motion was not taken into consideration. In terms of evaluation, only subjective viewpoints were collected.

Buoyancy Consideration

Buoyancy basics are necessary for PFD development. Both the volume and the placement of the floatation material need to be properly calculated and arranged.

In *On Floating Bodies*, Archimedes (c. 250 BC) suggested that:

"Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object" (Archimedes, c. 250 BC).

If expressed as a formula, buoyant force (F) is equal to the density (ρ) of the fluid multiplied by the fluid's displaced volume (V) and the gravitational acceleration (g), which is,

$$F=\rho\times V\times g$$

This is a common sense and the most basic principle that followed by scientists and researchers over a thousand years. As a result, to calculate the volume of floatation material needed to support the human body, it is critical to know the answer of following questions:

1. What is the density of water? What is the density of human body?
2. How much volume of the human body need to be supported by the PFD?
3. How much buoyancy is needed to support volume specified by question 2?

To answer the first question, as the widely known scientific and historical facts, water density is 1g/cm^3. This value would slightly change with temperature and atmospheric pressure (Table 4).

Table 4 Density of water, at standard sea-level atmospheric pressure

Temperature °F/°C	Density grams/cm^3
32 / 0	0.99987
39.2 / 4.0	1.00000
40 / 4.4	0.99999
50 / 10	0.99975
60 / 15.6	0.99907
70 / 21	0.99802
80 / 26.7	0.99669

Note: Reprinted from Perlman, U. H. (n.d.). Water Density. Retrieved from https://water.usgs.gov/edu/density.html

Besides, sea water has a higher density because of salinity in the water. According to *Encyclopedia Britannica*, it is conventional to express the density of seawater is equal to "grams per liter excess over one kilogram," designated by the symbol σ. In other words, the density of sea water 1025 g/L is expressed as σ of 25.

As for human, human body density has been investigating by many researchers for a relatively long period of time. Pascale et al. (1956) conducted a study with 88 soldiers and got the result that average density of 17-25 years old male is 1.068±0.012 g/ml. United States Army Medical Research & Nutrition Laboratory (USAMRNL) reported that the range of body density of an adult man is from 1.01-1.094g/ml based on data from 93 subjects (Allen et al., 1960). Harry et al. (1966) measured body density of 173 male adults; they found that body density decrease with age and the range of mean among all age groups is from 1.017-1.060g/ml (g/cm^3).

On the other hand, human body density is also determined by the status of the lung. Donoghue and Minnigerode (1997) calculated the specific gravity and buoyancy in both freshwater and seawater, at specified lung volume for each subject. Data obtained from 98 subjects indicated that all of them would be able to float in either freshwater or seawater at full lung capacity. At functional residual capacity, which refers to the volume of air exists in the lung at the end of passive expiration, 69% of the subjects could be afloat in seawater, while only 7% could float in freshwater.

To sum up, in most conditions, human body density is slightly higher than water since their lung are not always at full capacity. But since the difference is marginal, we could assume that human body is at the critical point of sinking and emerging. Consequently, any extra buoyancy provided by another device would lift the body to be emerged out of water surface. The volume emerged would almost be equal to the volume of the part of the device that sinks underneath the water.

$$(W+D)\times g = F = \rho\times V\times g$$

Here, W is human body weight while D represents the weight of the device, V = $V_{body} + V_{device}$, where V_{body} and V_{device} correspond to the volume of the body and the device that submerged under water, ρ is the fluid density. This formula leads to the second question, 'How much volume does human body need to be supported by the PFD?'

Researchers have explored the weight and volume of body segments by using different methods.

Harless (1962) weighed 44 segments taken from seven corpses and measure the volume of them by water displacement. According to his results, the head volume of a male is around $3453cm^3$, so if a human wants to lift his head above water, displacement of $3500cm^3$ water by the device is needed.

According to Clauser et al. (1969), head volume is $4418cm^3 \pm 350$, which is based on the study conducted with 14 cadavers that were divided into separate sections and measured.

De Leva (1996) concluded that head of a male takes 6.94% of the whole-body weight. This conclusion came from data of 100 male subjects with the average weight of 73kg and the average age of 23.8 yrs. Thus, a typical male subject in this sample has the head weight of 5kg, which need to be supported by $5000cm^3$ displacement of water.

Hereto, the 3 questions mentioned at the beginning of this section have been explained and relative theories have been proved with related literature. Findings of studies presented above concluded that the volume of most male adults' heads is less than 5000cm^3. Therefore, buoyancy aids, usually flotation foams or air bladder, should have volume more than 5000 cm^3 to offer the most basic support.

Thermal Comfort

As a type of protective clothing, thermal comfort is also an important consideration for PFD because it impacts rowers' athletic performance. Thermal comfort is usually referring to the microenvironment between the wearer's skin and the outermost layer of the protective garment that can be sensed and monitored by the neural system. (Sullivan & Mekjavić,1992; Muir et al., 2001; Bishop et al.,2003; Gao & Niu, 2004).

When being used above water, PFD performs like a normal protective garment. The microclimate when rowing in the outdoor environment is always being influenced by perspiration because of the vigorous activity. Thus, if rowers wear too many layers, their sweat would be retained inside the clothes and create discomfort. On the other side, in the harsh weather, rowers need to face coldness, wind, and sometimes rain or snow. Impacts from these unpleasant environment conditions need to be alleviated by protective garments.

To reduce the discomfort created by perspiration, it is important to know the regional absolute sweat data on the human body, as shown in Figure 3 (adapted from Smith and Havenith (2011)). Less thermal pressure should be applied to wherever seems to have high sweat level.

When being used underneath the water, usually, it should just perform the function of flotation. However, when it comes to the thermal aspects in cold water, the advanced function would be the capability of slowing heat loss rate of the wearer to lengthen survival time.

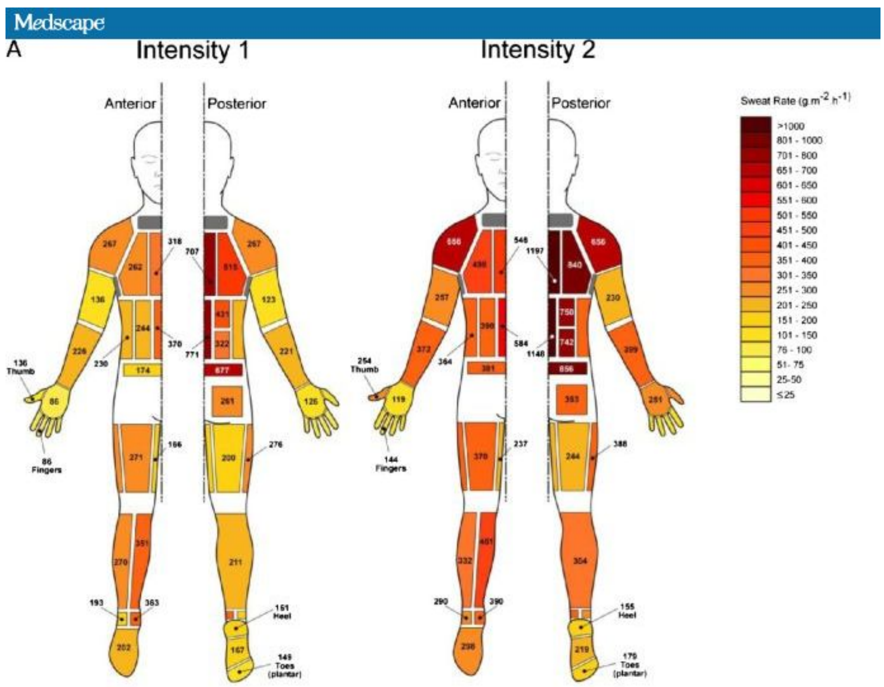


Figure 3 Regional absolute sweat data for male athletes (adapted from Smith and Havenith, 2011)

A few researchers addressed the effect of the garment on body heat loss during water immersion. Hayward et al. (1974) explored the association between heat production and water temperature at different activity status with light clothes and a life jacket. They concluded that: 1) metabolic rate has an inverse relationship with water temperature; 2) the thermogenic mechanism was less efficient in cold water, it cannot balance the heat loss of the body in cold water 3) they proposed the equation to predict survival time in cold water. However, this study focused on the prediction based on thermal balance and survival time, no data available for comparison to subjects immersed without the life jacket. It is impossible to know how much the PFD affect metabolic rate and heat loss while immersion.

The more relevant study was conducted by Tipton et al. (1990). To compare the protection provided by different clothing settings against cold shock response, 9 healthy subjects participated in the head-out immersion experiment in cold water with 3 different clothing assembles, which are swimming trunks only, conventional clothing, and conventional clothing plus windproof clothing. Significant differences were found in terms of mean skin temperature, respiratory frequency, and minute ventilation when comparing swimming trunks condition to the other two clothing assembles. Although no significant difference was proved, subjects' overall health in the last condition is slightly better after immersion into cold water. Data indicates that when subjects wearing the conventional and waterproof garment together, the mean skin temperature is higher at all time. Meanwhile, breath hold time is longer, heart rate and respiratory frequency are slightly more moderate. This study proved the function of thermal retention performed by layers covered on human body, even underneath the water. It is reasonable to assume that if subjects were wearing thicker layer as another garment condition, the physiology difference would become more obvious. Henceforth, a life jacket may help the wearer to maintain physiology function to some degree when being immersed into water.

In summary, considering the thermal comfort of the wearer, an ideal life jacket should offer adequate ventilation on areas that sweat a lot, while providing the function of thermal retention in water.

CHAPTER 3

METHODOLOGY

The theoretical framework of this study follows the Engineering Design Process (Lewis & Samuel, 1989) and Product Development Cycle (Carter & Baker, 1992) theories, which are summarized in Figure 4.

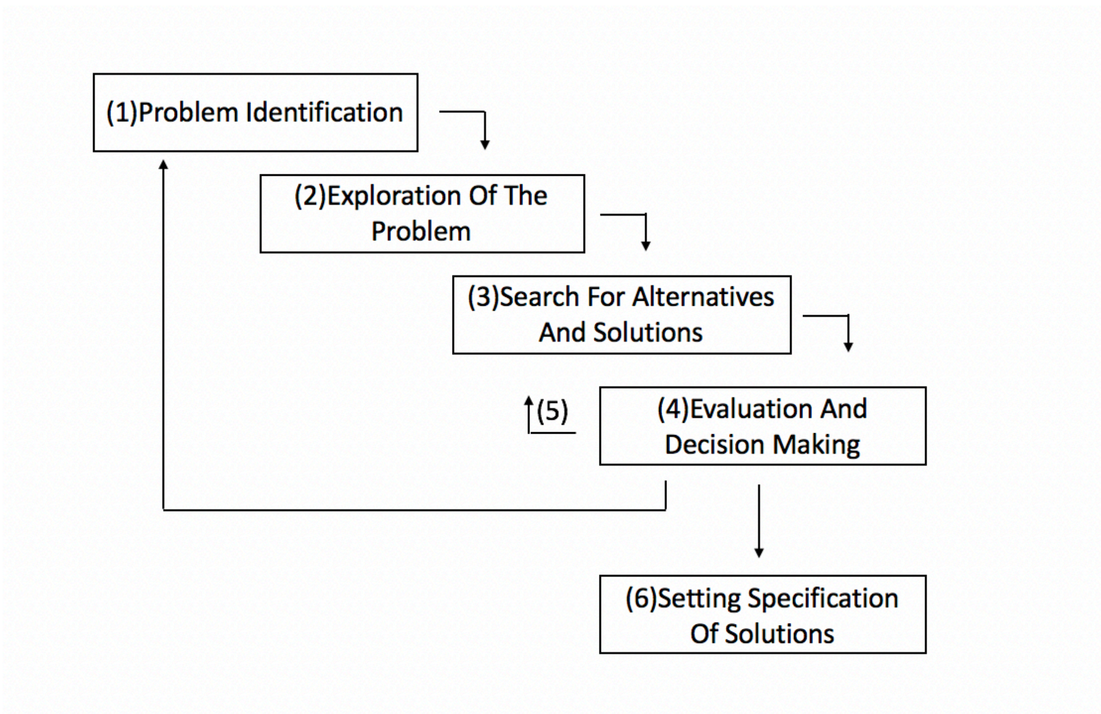


Figure 4 Theoretical framework of this study

This study consists of four phases – preliminary study, pre-test, prototyping, and post-test.

Preliminary study and pre-test in this study correspond to stages (1) and (2) (Figure 4) mentioned above, aiming to collect informative facts and scientific evidences to achieve the first two objectives stated in Chapter 1. Prototyping process was carried out while referring the pre-test results, along with the knowledge within the field of apparel design, textile, material application, ergonomic principles, and biomechanical basics. Evaluation of the prototype continuously interacts with the prototyping process accompany with trials and errors, which covers stages (4) and (5) stated in the theoretical framework.

The four-phase methodology is summarized in Figure 5.

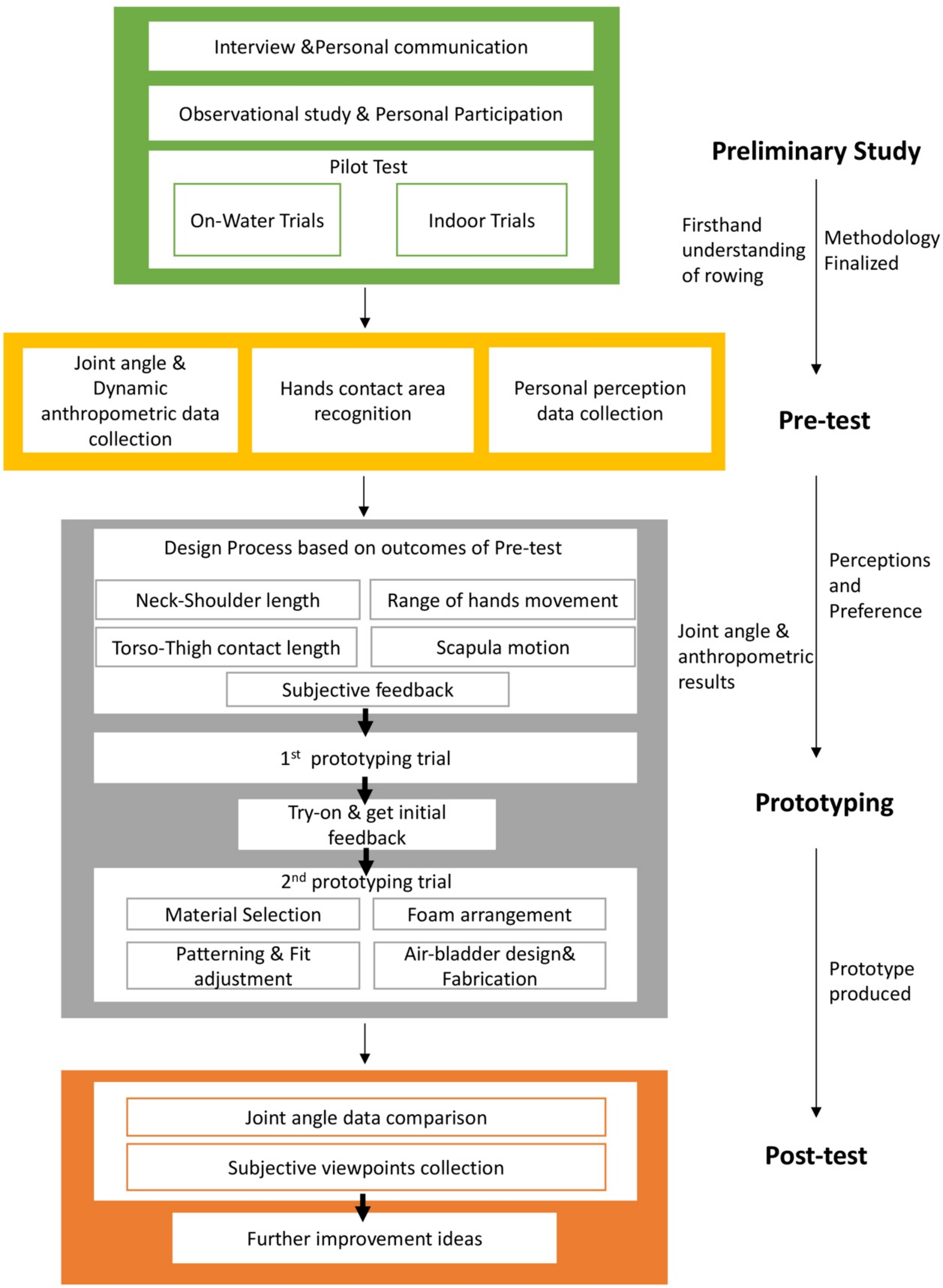


Figure 5 Methodology framework

3.1 Preliminary Study

Preliminary study was conducted to understand the sport of rowing, through personal communication with experts, observational study and personal participation in rowing practice, and pilot tests.

3.1.1 Interview/ personal communication

To better understand rowing culture and contemporary phenomenon for life jacket utility, personal communication with the head coach in Cornell Rowing, professional rowers, and coaches in a local rowing club were conducted between May and August 2016. At the same time, personal interview with a local rescue expert was done through personal meetings and email communication.

Personal communication includes conversations about the basic information about rowing team, current situation of PFD usage, accidents they acknowledged, influential factors impeding life jacket application, and environmental factors. Based on conversations with the head coach of Cornell Rowing, coaches in local rowing club and some elite rowers on campus, it is confirmed that rowers never wear a life jacket even in severe environmental conditions. This fact is due to the tradition of this sport, the belief of swimming skills of themselves, and the existence of chasing boats and coaches. (Personal communication, T. Kennet et.al, May, 2016). The common practice for safety concern in a rowing team is to have a necessary number of type I and II life jackets on the chasing boat. These life jackets are usually one size with the typical bulkiness. In fact, there have been accidents in recent years that required using the PFDs. For example, the most recent accidents at Cornell happened in 2015, a racing shell capsized when the outdoor temperature was about 40 F. Some rowers went to the hospital because of hypothermia. According to the head coach, on-water training would continue even though the ambient air temperature is below 40 ° F as long as no severe wind exists (Personal communication, T. Kennet, 2016).

The danger of rowing in cold weather is highlighted by Marc Messing, a veteran rower and Emergency Medical Technician (EMT) in Ithaca, N.Y, who has compiled evidences and data on rowing accidents on his blog 'RowSafeUSA' (http://rowsafeusa.org). He mentioned that all rowers are made aware of "cold-shock", a medical condition that can cause drowning in less than a minute, and that when that happens timely rescue cannot be satisfied by the reality of current response system. This is believed to be what caused the death of Mohammed Ramzan (2017) and John Steve Catilo (2004) mentioned in chapter 2. Besides, he also addressed that cold water is very dangerous since people would lose mobility in several minutes. Post-rescue collapse because of cold water also has been documented and supported by medical literature as one of the cause of death (Personal communication, M. Messing, 2016).

All personal communications with related experts laid the foundation of rowing safety context.

3.1.2 Observational study and personal participation

To understand the environment conditions for rowing. multiple visits to Cornell Boathouse for the competitions (Figure 6) were made during April and May in 2016. Observations basically include the structure of boats, the garments they were wearing, and how rowers interact with racing shell.


Figure 6 Preparation for rowing competition

Rowing is a unique sport, and it is hard to be understood solely by objective information and descriptions of other people's experience. As a design researcher, it is critical to have a firsthand feel of the needs for equipment and garments from a rower's perspective in order to achieve better functional design. As a result, a 3-week personal participation of an adult 'Learn to Row' courses was taken during July and August 2016.

Figure 7 Personal Participation of Rowing with a Coach

The classes focused on single sculling boats with two oars applied in practice. Coaches taught rowers basic rowing techniques, and the targeted achievements of this program are independently launching boat and rowing without guidance. During the process, proper techniques for rowing in racing shells were obtained, while a better understanding of this activity and the personal experience of capsizing accidents were achieved. (Link to the program website: http://www.cascadillaboatclub.org/learn-to-row.html)

3.1.3 Pilot Test

Two pilot tests were conducted both on water and in the indoor environment for the aim of finalizing the methodology.

On-water trial

Higher stroke length will generate more energy output and higher relative speed, thus, it is very critical for elite performance. Traditional life jackets always have foam in front of the chest area, which inhibits their hands movements towards the body and results in shorter stroke length. To reduce such negative influence from PFD, it is important to know the range of movement of their hands near chest area (Figure 8.).

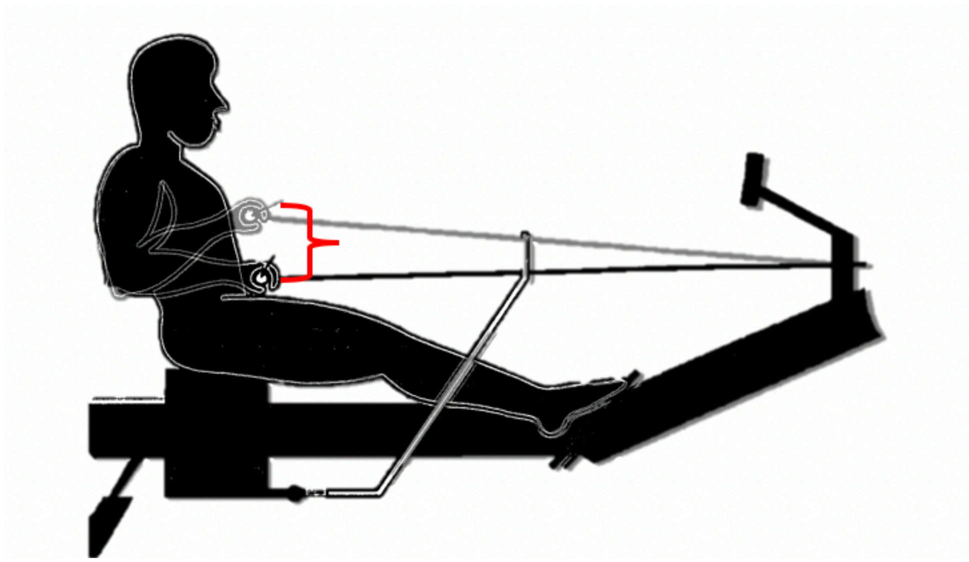


Figure 8 Demonstration of hands movement range near chest

To explore where exactly the hands move around chest area, the initial idea is to conduct a ‘contact test’ - let the subject wear a white tank while putting ink on their hands and forearms. During the on-water rowing, the ink will dye the tank shirt at where hands get in touch with the torso. Thus, the hand's vertical movement range near chest could be estimated.

Figure 9 Identification of contact area

Figure 10‘Contact test’ on water

After carrying out this pilot test in the outdoor environment, outcomes of this pilot test suggest that: (1) environmental condition is not consistent, as a result, the results will also depend on the weather and water conditions; (2) because of the location and availability of the boathouse, execution of multiple tests would be unrealistic; (3) such tests always need coaches' monitor and accompany; (4) too much unpredictable risk.

Henceforth, although the results from this pilot test are very informative, a more stable indoor environment was needed to consistently control the test condition and conduct multiple tests.

Indoor trial

To explore the difference of rower's range of motion when they are with and without a life jacket, a pilot test using a portable 3D scanner while rowing on the ergometer was conducted to confirm the feasibility of this method.

As showed in Table 5, 3D scans of a rower in 2 garment conditions (with and without a life jacket) and two postures (Catch and Finish) were carried out on an ergometer.

Table 5 Indoor pilot tests

Condition	Pictures	
Indoor rowing trials		
3D scan without life jacket	 Catch	 Finish
3D scan with Life jacket	 Catch	 Finish

3.2 Methodology

To investigate the influence of traditional PFD on rower's range of motion and further compare with the prototype, it is important to have real rowers as human participants for joint angle and anthropometric data collection in this study. On the other side, elite rowers have better understanding of the environmental and behavioral factors, their opinions are more informative than just random human participants. Since light-weight rowers have more similar body shape with the average population, for better application to amateurs, beginners and other non-elite rowers, it is better to start this study with them instead of the heavy-weight team.

Therefore, the pre- and post- test, the inclusion criteria for human participants are consistent:

1) Those who are 18 - 30 years old.

2) Those who don't have any known orthopedic health issues which may affect body movement.

3) Those who don't have any known dermal symptoms.

4) Those who are experienced light-weight rowing athlete with rowing experience more than two years.

Data of joint angle through 3D scan, hands movement through video recording, and subjective opinions through structured questionnaire were collected. The study was approved by Cornell Institutional Review Board for Human Participants with the protocol ID 1610006702. The detailed procedures for each section will be described in the following content.

3.2.1 Pre-test

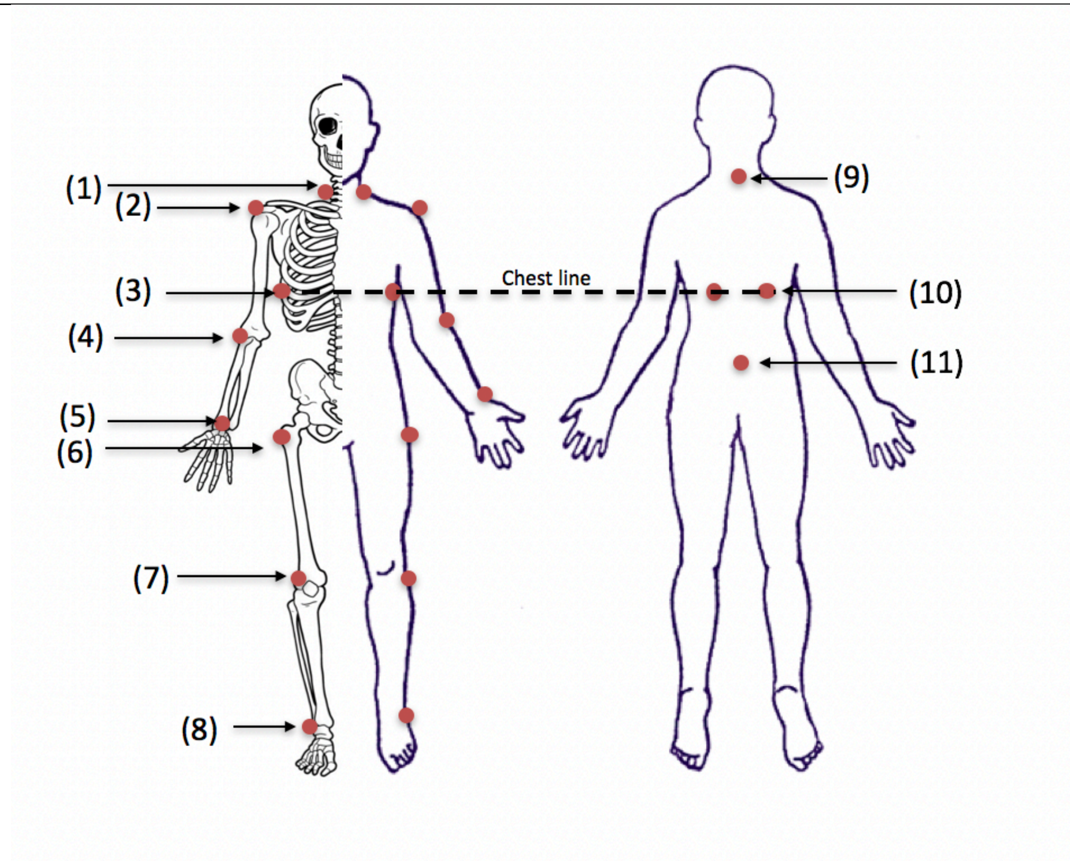
Pre-tests were conducted in Cornell indoor rowing training center located in Teagle Hall. A portable 3D scanner (Structure Core, Occipital, San Francisco, USA) was used to conduct scanning and a digital camera with a tripod were used for video recording.

Three sessions are conducted to collect data correspondingly: (1) joint angle data through 3D scan; (2) hands movement range through video recording; (3) subjective opinions through a structured questionnaire.

Joint angle and dynamic anthropometric data collection

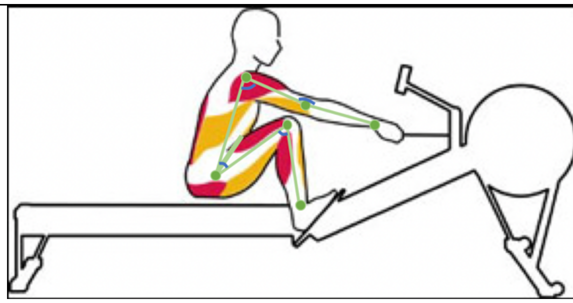
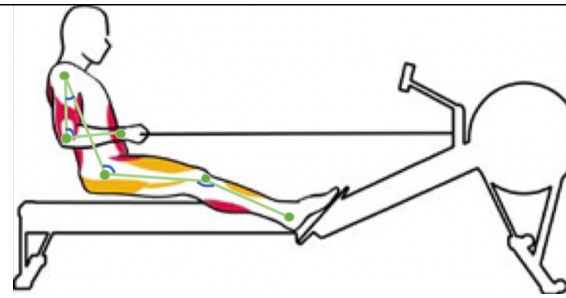
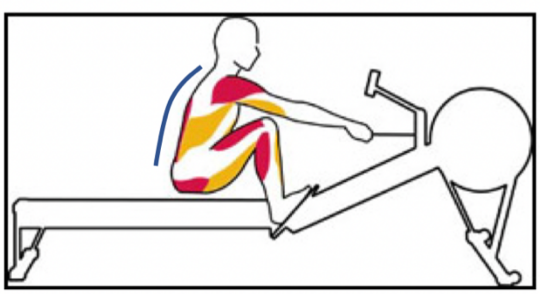
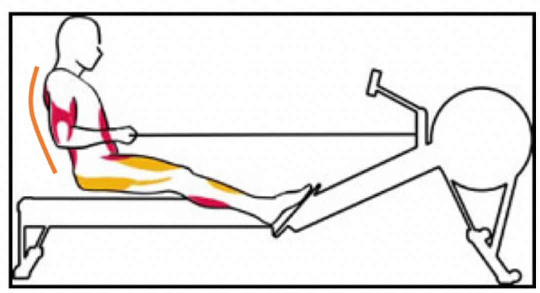
20 markers (Table 6.) indicated critical points that have anthropometric reference on subjects' body were set before processing scanning. After finishing several strokes, each participant was asked to stay still (for about 2~3minutes) in 2 critical postures of rowing (Catch and Finish) to be scanned. Then they were asked to wear a traditional PFD and went through the same procedures again. This session was conducted as same as the indoor pilot test.

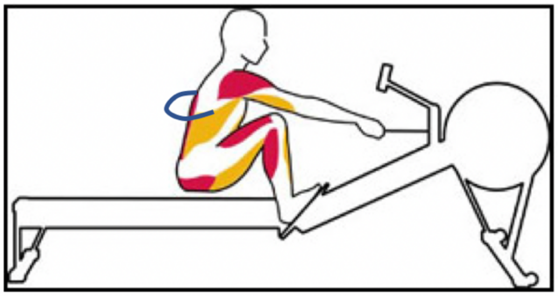
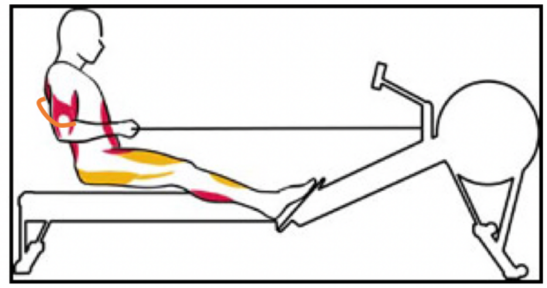
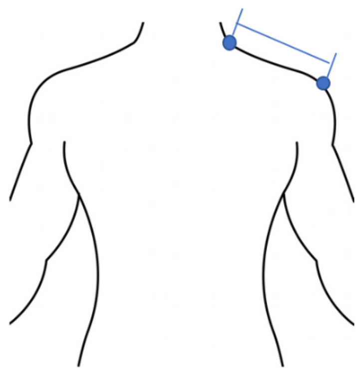
Table 6 Markers setting for 3D scanning

Front view		Back view
(1) Side base of neck (2) Acromion (3) Middle point on the side on chest line (4) Lateral side of Elbow (5) Back side of wrist joint (6) Lateral side of Great Trochanter (7) lateral side of the knee bone (8) Lateral side of ankle joint	 	(9) 7th cervical verteb (10) 2 markers on bac the chest line to help chest level identificati (11) Intersection of sp and waist line

After scanning, scan files were processed and analyzed by a 3D software from Geomagic® company. Joint angles and other anthropometric measurements were taken through this process. Measurements obtained from this session and their definition listed in Table 7.

Table 7 Joint angle and dynamic anthropometric measurements

Position	Catch	Finish
Joint angle	 Angle between arm and torso; angle between upper-arm and forearm; angle between torso and thigh, and angle between thigh and calf; contact length between torso and thigh*	 Angle between arm and torso; angle between upper-arm and forearm; angle between torso and thigh, and angle between thigh and calf.
Back Length	 Back length from 7^{th} cervical vertebra to waist line along the spine	

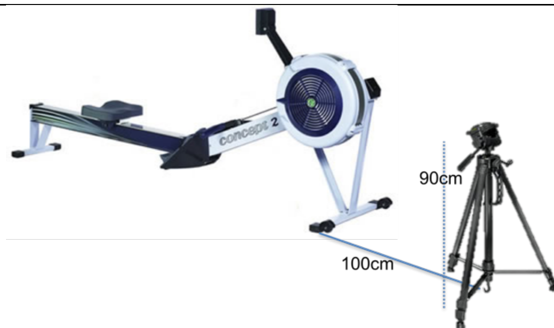
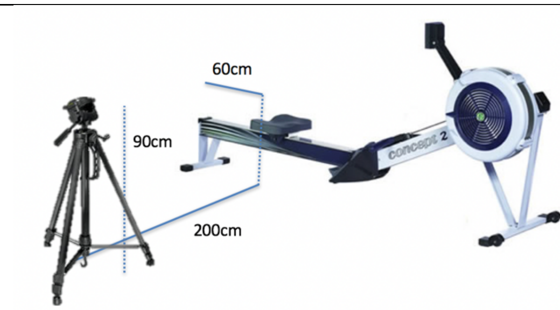
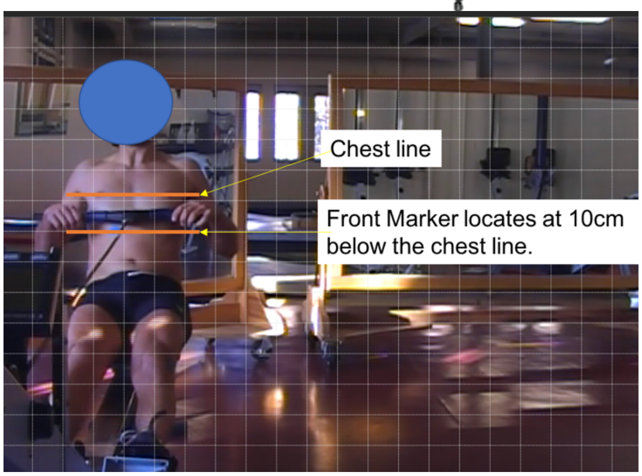
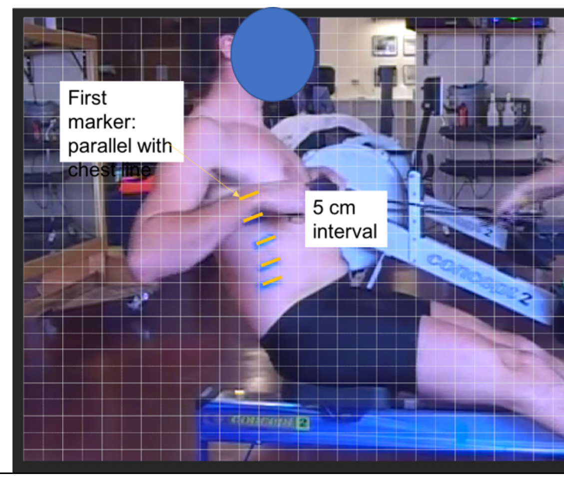
Half chest circumference on the back side (referred as HCB)	  Half chest circumference on the back side measured from one side-body markers (marker (3)) to the other one along chest line.
Half-shoulder length	 Half-shoulder length from neck line to acromion along the shoulder.

Note*: Contact length here defined as the length at the right sagittal plane from hip joint till where the contact area ends.

Hands movement range recognition

A digital camera was set relatively to the position of the ergometer to record rowing motion. Markers were put on the front and right side of the torso as the distance reference for video analysis. Video recording from back view is just for observation of body parts movement instead of obtaining quantitative data. The settings of digital camera and markers in the front and back view were demonstrated in Table 8.

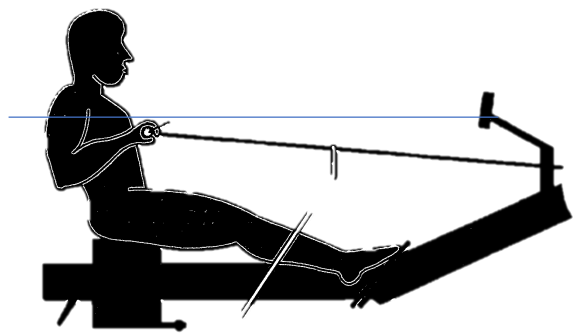
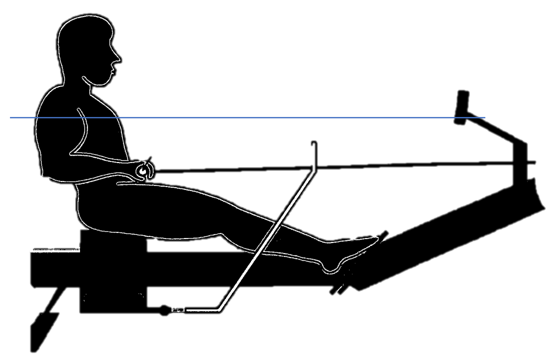
Table 8 Settings for video recording

	Front view	Right side view
Camera settings		
Markers settings		

During the video recording, rowers were asked to row at their standard training stroke rate (around 20~22 strokes/min), 4-minute videos were taken from front and side view of the subject while a 2-minute video was taken from the back view.

For each participant, five touching and leaving points (Table 9.) within each stroke were found in Photoshop® software in front and side view video trials. With the aid of grid background (Figure 11 and 12), the vertical distances between their hands and chest line were estimated and recorded for data analysis. To reduce deviation, the average value of 5 points for each video trial were calculated as the participant's record.

Table 9 Range of Handle Shift

Name	Demonstration & Definition
Touching point	 The point when the rower's hands are closest to their chest but have not started to tap down.
	 The point when the rower's hands are lowered to the lowest level but have not been moved away from torso.

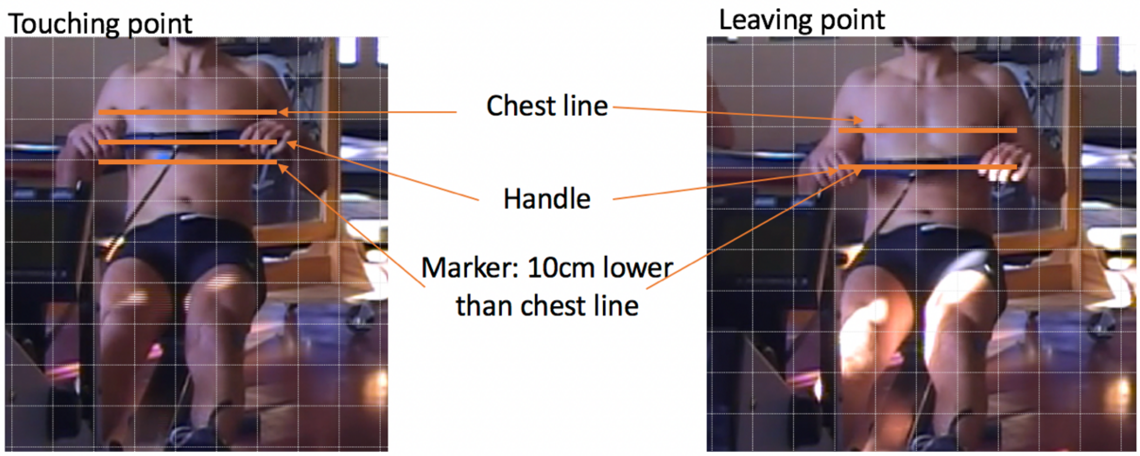


Figure 11 Measurements of hand movement range - Front View

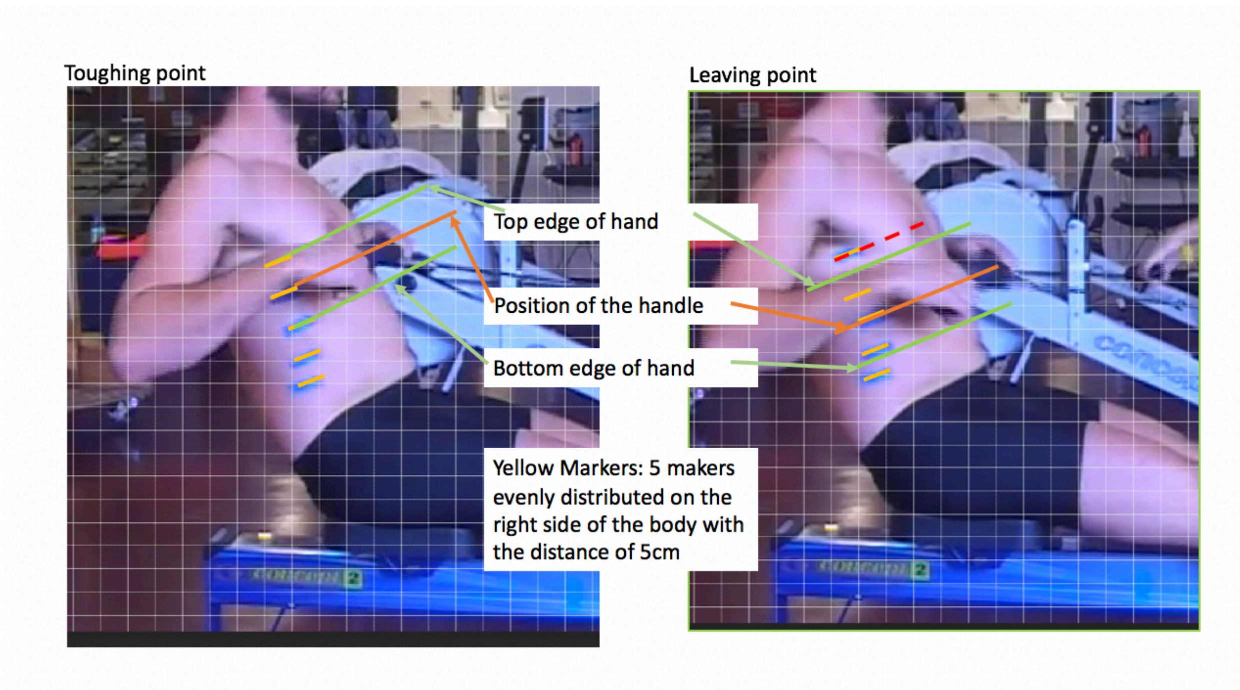


Figure 12 Measurements of hand movement range - Side View

Perception data collection

Perceptions of PFD, behavior of wearing it, and comfort level of the traditional PFD used in this test were collected through a structured survey, which includes two parts – phase I personal experience questions and phase II perceptions of test PFD. Before trying on the given PFD, subjects were asked questions about their experience of PFD wearing and some other general questions (like swimming skills, perceptions of rowing, see appendix 1.). After their wearing of the traditional PFD, their perceptions of mobility, tactile and thermal comfort of test PFD were investigated by the rest part of the questionnaire.

3.2.2 Prototype development

Prototype development is based on the data and feedback obtained from pre-test trials.

Design process based on outcomes of Pre-test

There is always a constant body dimension change, even during a simple motion. The deformation happens on the skin surfaces and the dimension of muscle informs body the corresponding of anthropometric measurements. An activewear is supposed to appropriately accommodate body changes during movement (Choi & Ashdown, 2011; Gill & Hayes, 2012; Wang, Mok, Li, & Kwok, 2011). Henceforth, consideration of body motion and dynamic anthropometric measurements is very important for PFD design, especially for some specific body area where want to be free of the impact of life jacket.

1) Half-shoulder length

During rowing, shoulder length keeps changing because of the protraction and retraction motion of scapula. It is important to know how much such the half-shoulder length changes to design shoulder straps with an appropriate width so as to reduce restriction and rubbing caused by the garment. Subjects' half-shoulder length obtained from Geomagic® software shown below in Table 10.

Table 10 Summary of Neck - Shoulder Length

	Catch （cm）	Finish(cm)
Mean	0.12±0.01±0.0069	0.15±0.02±0.0069
Min.	0.108	0.116
Max.	0.126	0.189

On average, shoulder width shrinks about 3cm in catch position compared to the finish position. Minimum shoulder width is 10.8cm among all observations. While moving, each side of the strap should have enough space to prevent rubbing with neck and shoulder skin. As a result, the shoulder strap should be less than minimum half-shouler length and should accommodate shoulder movement.

2) Range of hands movement

Hands movement is critical since it will further affect the trajectory of oars which generate force for the whole unit. Therefore, it is crucial to keep hands motion unaffected. In the video analysis session, the range of hands shift (shown in Table 9.in pre-test methodology) near chest area in the finish position has been investigated. Thus, the area in the front chest where less foam should be placed has been concluded.

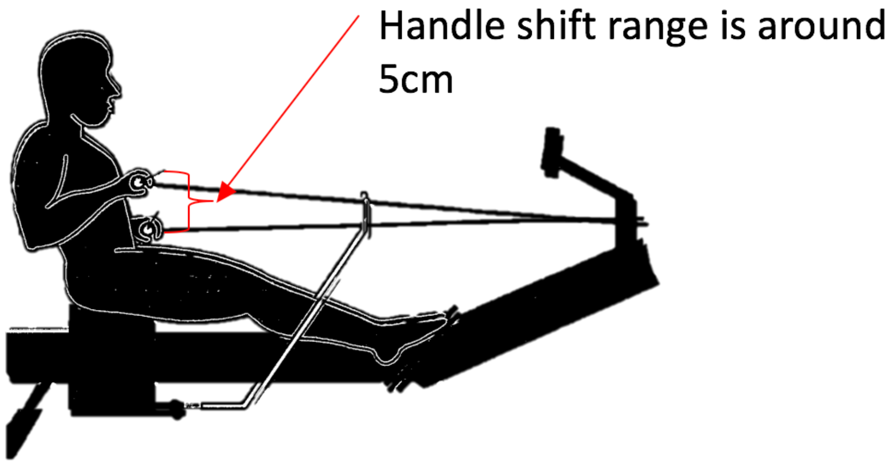


Figure 13 Range of Handle Shift

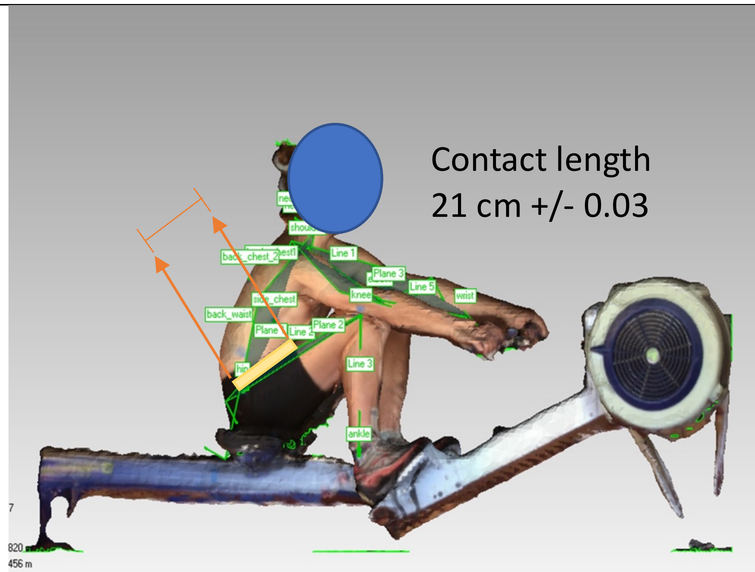
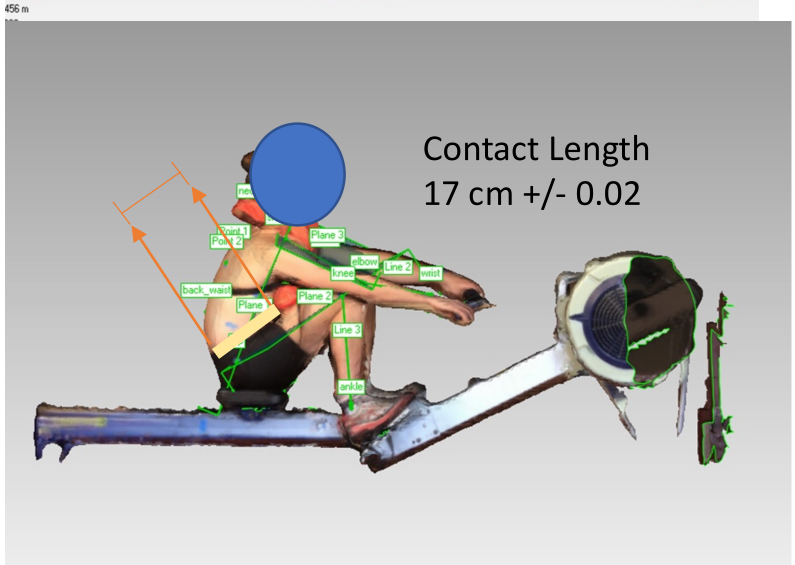
3) Thigh and Torso Contact Length

The interference at the abdomen area will affect a rower's performance through shortening the stroke length and reducing body balance due to the conflict between hands and oars. Thus, the scope of the area where under influence is a significant reference for foam arrangement design at the abdomen.

The contact length between torso and thigh in this context defined as the length at the right sagittal plane from hip joint till where the contact area ends (as mentioned in Table 3). In the catch position, the contact length between torso and thigh was compared when the rower is wearing and without the life jacket.

As shown in Table 11, reduced contact area appears with the use of traditional PFD, which means a larger angle between torso and thigh. It is confirmed in chapter 2 that adequate range of movement for lumbopelvic flexion is important to achieve better power output and longer stroke. Therefore, enough contact area should be provided to achieve maximum torso bending in the catch position.

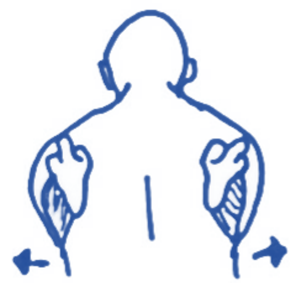
Table 11 Contact length with and without life jacket

Conditions	Demonstration
Without Life jacket	
With Life jacket	

4) Scapula motion

Through observation of the back-view video, it is found that major motion of scapula is retraction and protraction.

Table 12 Scapula motion of rowing

Video record	Category of motion
	
	

Note: Figures from “Level3(69) Exercise and Fitness Knowledge: The shoulder girdle”, Retrieved from from http://amactraining.co.uk/resources/handy-information/free-learning-material/level-3-exercise-and-fitness-knowledge-index/level-3-69-exercise-and-fitness-knowledge-the-shoulder-girdle/

5) Subjective feedback

From interviews, some comments from rowers were highlighted and should be considered in the design of a rower-friendly life jacket.

For the traditional PFD, subjects complained about that shoulder movement has been restricted by the test PFD; pressure on the chest and neck area is not comfortable; and they don't like the strap design, which rubs their back during rowing (As shown in Figure 14.)

Among all eight life jackets I offered, the top 3 they chose presented in Figure 14. They are a T-shirt-like inflatable life vest, a highly-segmented foam life jacket, and a normal inflatable PFD (Figure 15.). This result suggests the possibility to let them accept foam PFD as long as the foam is flexible enough and not restrict their motion too much. Besides, the combination of traditional foam PFD and inflatable PFD might be a good option.

Considerations above would be reflected in prototyping trials.

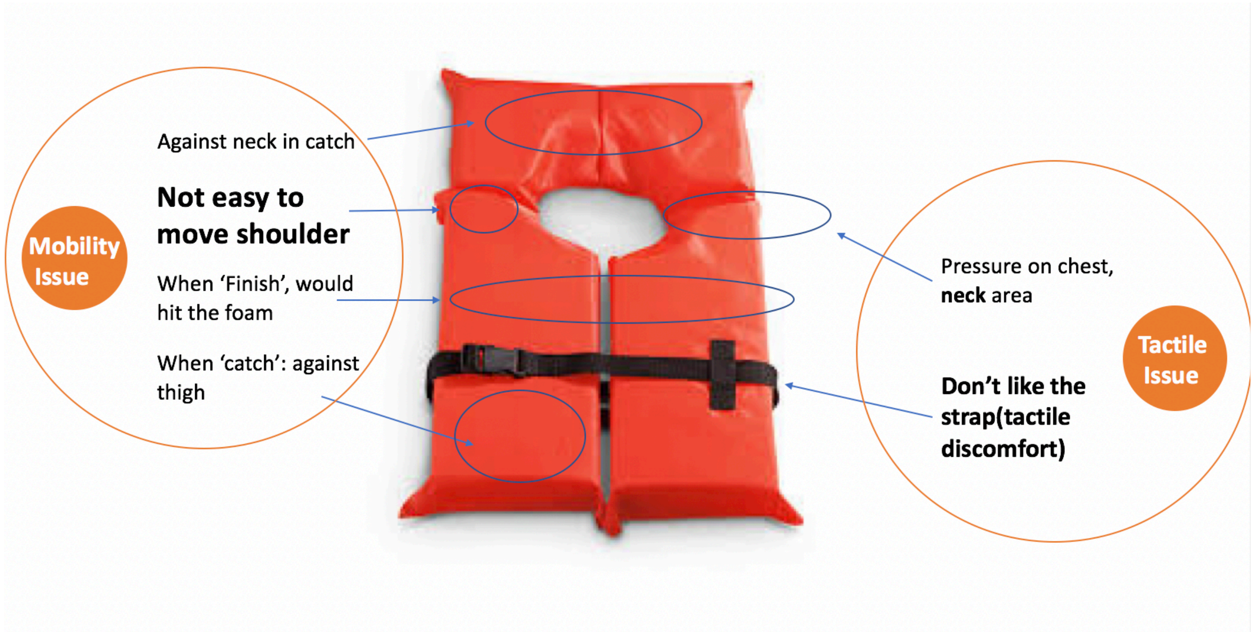


Figure 14 Major feedbacks on the test Type II PFD(Type II PFD figure from: http://guide.sportsmansguide.com/buyers-guides/life-jacket-vest-preserver-buying-guide/, edited by the author)

Figure 15 Top 3 of the rower's favorite PFDs (Figure from(Left to right): https://www.amazon.com/Float-Tech-Sea-Tee-Inflatable-Guard/dp/B00GMO8KRS; http://cargocollective.com/ACID/Flobo-Life-Jacket; goolgle image)

First prototyping trial

Goals of the first prototyping trial can be summarized as 3 points:

1) Try out the segmentation idea

2) Practice the construction methods

3) Preliminary application of data

This prototype was constructed with a base layer (a commercial vest), and the foam section (polyethylene foam) covered by a three-layer GORE-TEX® breathable and water-resistant fabric. Foam sections were fixed by sewing the water-resistant fabric onto the base layer. Inspired by the triangle foam segments from the 2nd favorite PFD picked by rowers, the first prototype applied triangle shape onto upper-torso to achieve better flexibility. Meanwhile, it was expected to have less impact on shoulder movement. On lower torso area, bar-shaped segments were used to accommodate bending motion on the lumbar and abdomen area.

After finished the construction, two try-on sessions were conducted with a standard size M dress form and a human subject for examination of fit and foam placement.

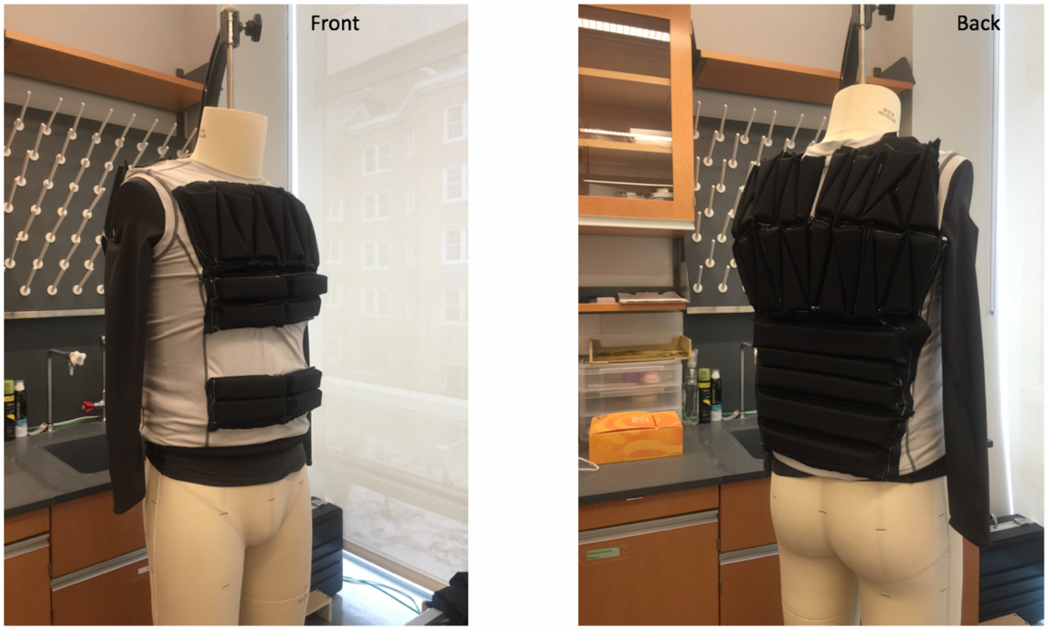


Figure 16 First Prototype on the dress form

Figure 17 First Prototype on human

Feedbacks from the first try-on session are summarized as Table 13.:

Table 13 Feedbacks of the first prototype

Positive feedback:	Problems & planned improvement in next trial
1. Easy to move, especially front chest and lumbar area. 2. Space for hand movement also provide flexibility on abdomen area, which let subject feels good 3. Snug fitting and stretch fabric are comfortable.	1. Too many unnecessary segments on the back, which makes it looks a bit weird. 2. The waterproof fabric is heavy; foam is stiff 3. Sewing is not the perfect way to construct foam onto the base layer 4.Side opening is preferred for easier donning and doffing (Based on rowers' opinion)

Based on these feedbacks, the second round of prototyping is going to improve the problems and apply positive attributes from the first prototype.

Second prototyping trial

For the second prototype, new types of material were used for both the base layer and the foam. Based on market research, two types of foam (Normal and Cross-Linked Polyethylene) listed in Table 14. were the most appropriate material for floatation devices.

Table 14 Comparison of foam material

Type	Density (lbs/ft^3)	Firm / Soft level*	Thickness	Other features
Polyethylene	1.2/1.7/2.2	Soft ((25% PSI-7)	1/4 - 4	• Shatter proof • Non-dusting • High shock absorption • Superior chemical & grease resistance • Antibiotic Features
Cross Linked Polyethylene	2	Soft (25% PSI-6)	1/4- 2	• Resilience • Superior buoyancy • Good thermal insulation • Excellent strength and shock absorption • Low water absorption • Antibiotic Features • Excellent chemical resistance • Nontoxic and contains no CFCs, HCFCs, or hydrocarbon blowing agents

*lower the PSI value, softer the foam
Note: Part of information referred from the data sheet of Foam Factory, Inc.

Furthermore, after consultant with experts who deals problems in the field of material science, it is confirmed that cross-linked polyethylene(PE) has better quality and more durable regarding sustained usage (Personal communication, A. Netravali, 2017). As a result, it was selected as the floatation foam for the second prototype.

As for the base layer, a Nylon-Spandex tricot (80% nylon, 20% spandex) was used for the front and back panel while Nylon-Spandex Power Mesh (85% nylon, 15% spandex) as the side panels. Both materials are very stretchy and can be durable when used in water.

1) Base layer pattern making

Base layer pattern was following the basic pattern making methods for stretchy fabric. The pattern was revised twice for relative tight fitting on the size medium dummy with 36 inches' chest measurements. Besides, the neckline was further widened and deepened for shoulder and neck comfort.

Figure 18 Base Layer Pattern

2) Foam arrangement

The foam arrangement was the process of application of pre-test data. Based on the results and interpretation from pre-test, design considerations were applied onto foam segments design.

To accommodate the 'handle shift range' near the chest area and further minimize the adverse effect from the foam, a 'Foam-Free' area was determined with the heights of 7.5cm and the position 5cm lower than the chest line, which covers where the hands shift around.

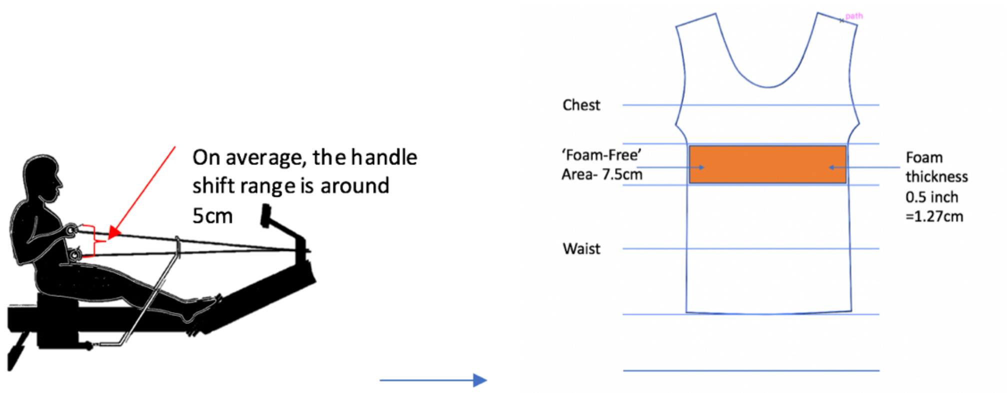


Figure 19 Determination of 'Foam-Free' area

To realize maximum bending of the torso in the catch position, the contact area where thigh and abdomen could get in touch should have a minimum amount of foam. As shown in Figure 20., about 20cm above the hip line should not have foam so that rowers can achieve maximum bending.

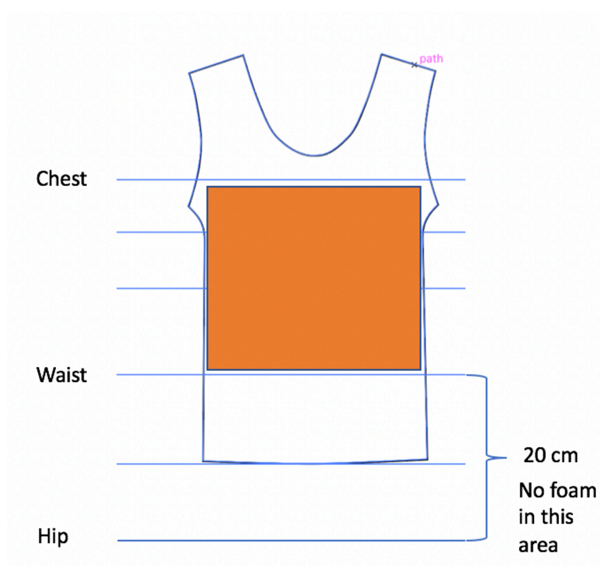


Figure 20 Eliminated foam placement for maximum contact area

Foam placement was also designed with the consideration of scapula position and retraction and protraction motion.

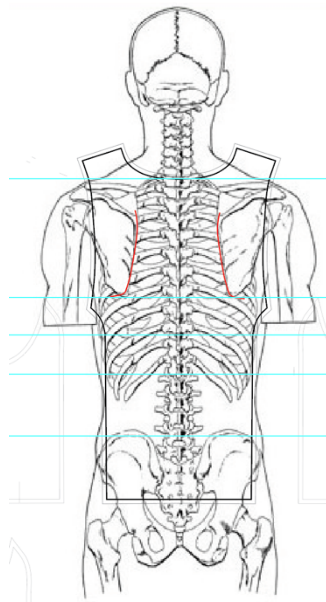


Figure 21 Consideration of scapula position

With all the factors above and other human torso movement natures, the final design of foam placement is presented in Figure 22. Back foam segments on upper-torso were placed based on scapula motion while sections on the lower back were placed by bar-shaped for the convenience of bending at lumbar area. Foam on the front panel has been put with aforementioned considerations (handle shift range and contact length). The two triangle-shape segments on chest area were inherited from the first prototype for better flexibility. The green bars in the “foam-free” area have only 0.5-inch thickness. The total volume of foam is 3350 cm^3.

Figure 22 Foam placement arrangement

3) Air bladder design

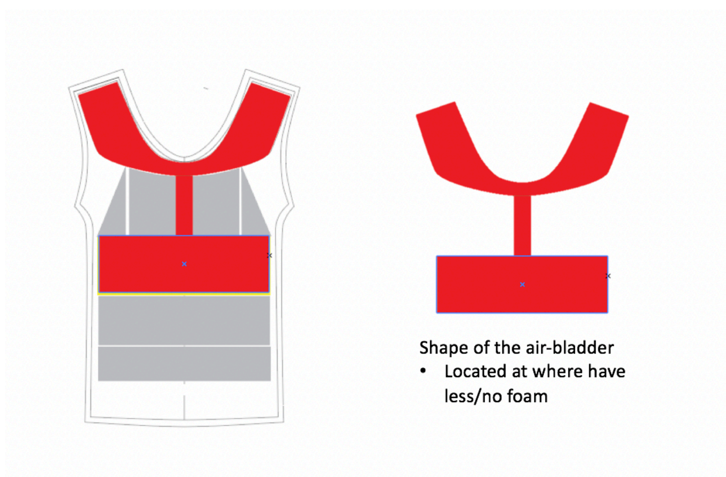


Figure 23 Air-bladder design

For enough floatation on the front panel, additional buoyancy aid is needed. Therefore, an air-bladder was designed to be placed on the front panel. The shape of this bladder based on the placement of foam. In general, the air bladder locates where has no foam or fewer foam layers compared to other places.

4) Execution

The base layer fabrics are cut by hand and panels were constructed by the zig-zag sewing machine to ensure stretchability.

The cross-linked PE foam was cut with laser-cut machine following the pattern designed for foam segments. As shown in Figure 24., grey sections on the back were piled up by four quarter-inch layers for each of them. For the front panel, the green bars in the "foam-free" area have only two quarter-inch foam layers while the middle two parts above it have five layers. All other sections on the front panel have four layers just like the back panel.

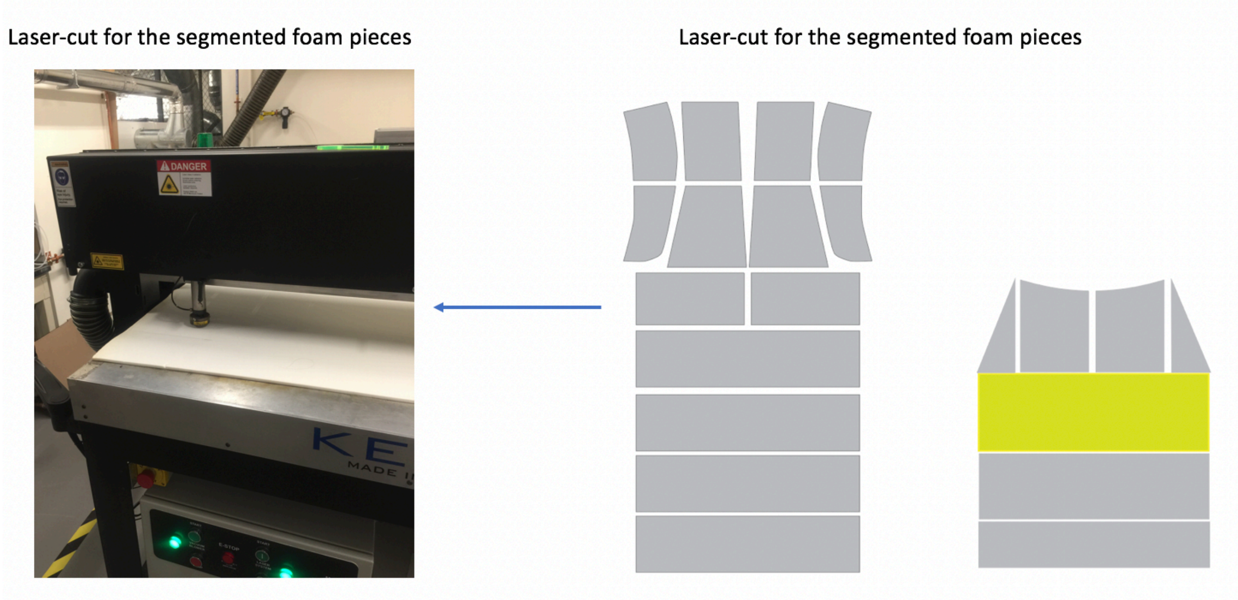


Figure 24 Foam fabrication

Foam segments were connected and fixed by flexible straps made from a white power mesh fabric (Nylon and Spandex blended) to create a flexible structure. Straps sewn onto the base layer is for the insertion of foam layers.

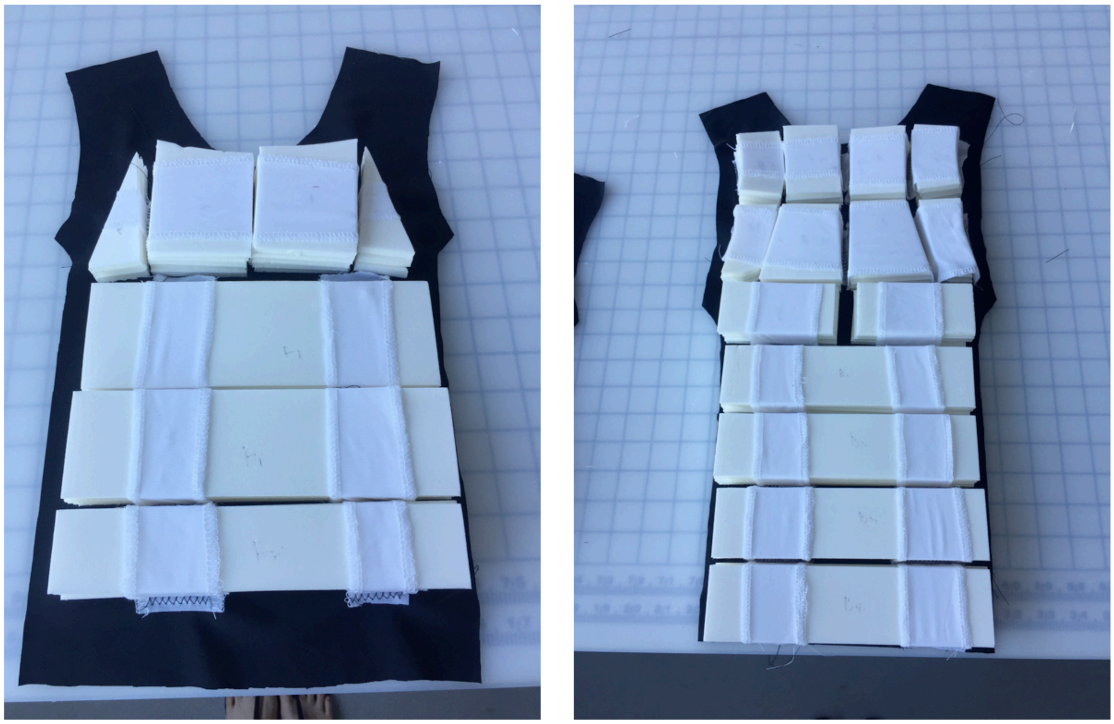


Figure 25 Foam construction

For water-splash repellent and wind resistant function, another waterproof coating fabric was covered on the top of foam segments as shown in Figure 26.

Figure 26 Waterproof covering on the top of foam

Fabrication a customized shape air-bladder went through the trials and errors process. Table 15. listed all the material and method combinations have ever been tried and the reason they were not working.

Table 15 Trials and errors for air-bladder fabrication

Material + Method combination	Reason of failure
Water-proof material + Sonar bonding	Sonar bonding is too weak to be water tight
Water-proof material + Tape binding machine	Fabric is too weak, tape binding cannot curve
TPE/TPU+ Tape binding machine	Cannot seal curve edges
TPE/TPU+ Super glue	Cannot be tightly sealed
TPE/TPU+ silicone glue gun	Silicone glue cannot work on TPU/TPE
TPE/TPU+ iron	Too easy to melt TPU/TPE in the wrong way

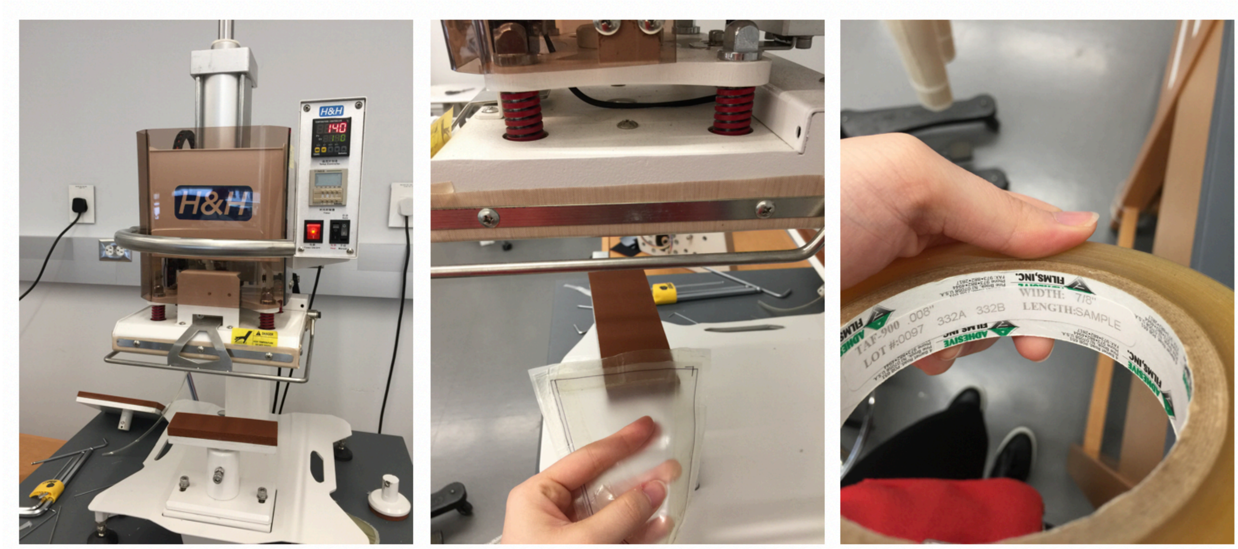


Figure 27 Heat-press machine and PVC tape

A Heat-Press machine and a PVC Tape with low melting point were finally applied successfully, and the air bladder was made as shown in Figure 27. After finishing it, the air bladder went through the leaking test, and the volume of it was measured by measuring the volume of water displaced by the inflated air bladder. The result is 1400cm^3.

Figure 28 Inflated Air bladder

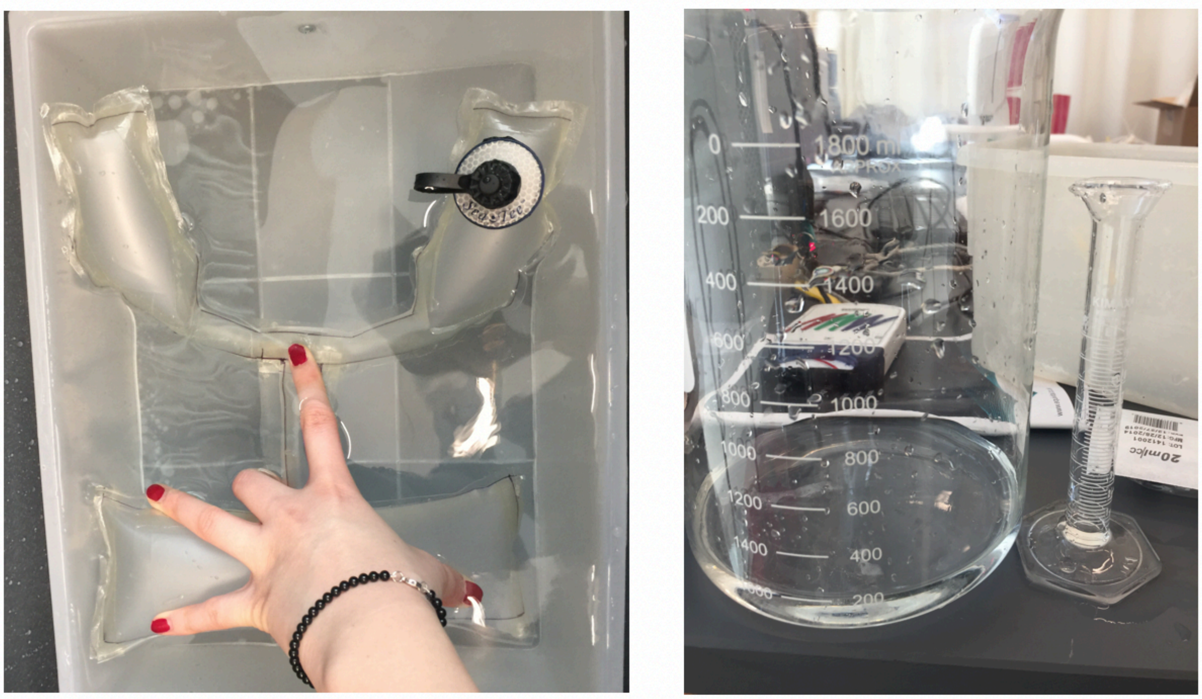


Figure 29 Leaking test and volume measurement

The air-bladder was inserted underneath the front panel by attaching onto another panel, which was later connected to the top front panel through sewing the edge of two panels.

Figure 30 Panel underneath the front layer

Finished version of the second prototype from different views presented in Figure 31 and 32.

Figure 31 Deflated Prototype 2 from different views

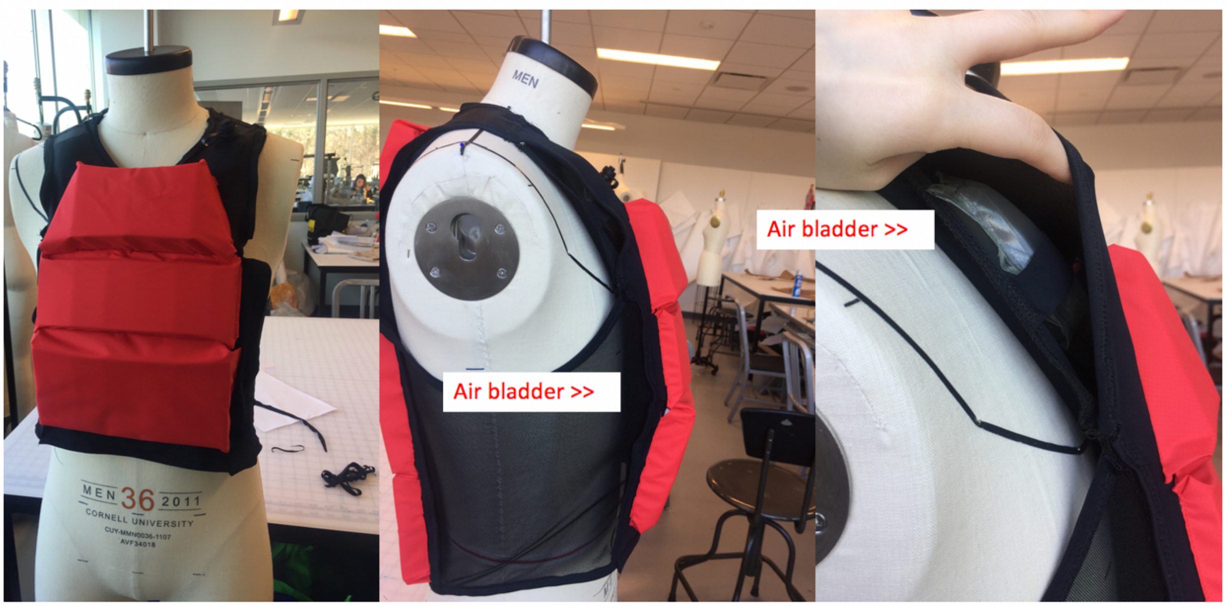


Figure 32 Deflated Prototype 2 from different views

3.2.3 Post-test

Although feedbacks of the prototype were continuously collecting by informal interviews during prototyping process, the formal post-test with exactly same subjects and location as the pre-test was conducted at the end of prototype construction. The process only includes the 3D scan and interview session adapted from the pre-test. The same portable 3D scanner (Structure Core, Occipital, San Francisco, USA) was used to conduct 3D scanning and a structured survey designed for the post-test was employed in the interview.

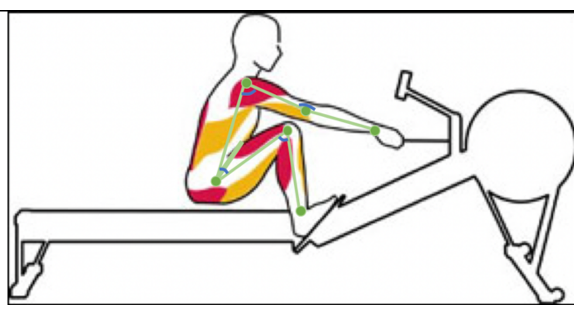
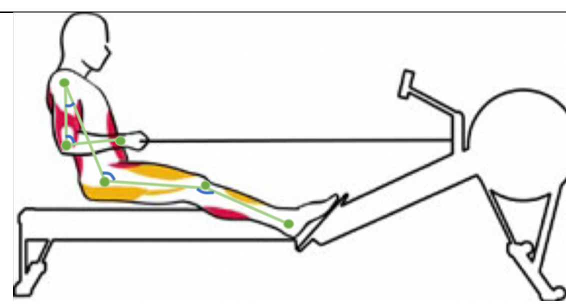
Two sessions were conducted with the similar procedures as pre-test to collect necessary data:

1) Joint angle data collection

Markers on the joint of their body were set before process scanning (same as Table 6. for pre-test), and they were asked to wear the prototype PFD. After finishing several strokes, each participant was asked to stay still (for about 2~3minutes) in 2 critical postures of rowing (Catch and Finish) to be scanned.

After scanning, scan files were processed and analyzed by the same 3D software from Geomagic® company. (Table 16.).

Table 16 Post-test joint angle measurements

Position	Catch	Finish
Joint angle	 Angle between arm and torso; angle between upper-arm and forearm; angle between torso and thigh, and angle between	 Angle between arm and torso; angle between upper-arm and forearm; angle between torso and thigh, and angle between thigh and calf.

	thigh and calf; contact length between torso and thigh*

Note*: Contact length here defined as the length at the right sagittal plane from hip joint till where the contact area ends.

2) Subjective viewpoints collection

The interview was conducted with a constructed questionnaire. See appendix 2.

In this session, the time they used for donning and doffing was recorded. After rowing while wearing the traditional and prototype PFDs, questions related with ease of use, mobility, tactile and thermal comfort were asked.

CHAPTER 4

RESULTS AND DISCUSSION

This study have recruited 7 elite light-weight male rowers from Cornell Rowing Team (age: 20.7±1.4 , height: 185.04±4.79, weight: 74.77±3.12, BMI:21.89±1.75, Chest circumference: 96±4.42, rowing experience 5.5±1.73 yrs). Participants' body shapes are similar and all of them wear size M for top. All subjects participated in the pre-test, while only 6 out of 7 participated the post-test.

4.1 Pre-test results & analysis

Pre-test aims at collecting data to achieve the following purposes:

1) identify needs for improved mobility and overall comfort during rowing.

2) identify the impact of wearing traditional PFD on rowers' motion and performance.

4.1.1 Joint angle comparison

Assumptions for catch position

Based on literature review about rowing techniques and biomechanics basics, accompany with personal rowing experience, assumptions about body angle change proposed as demonstrated in Figure 33.

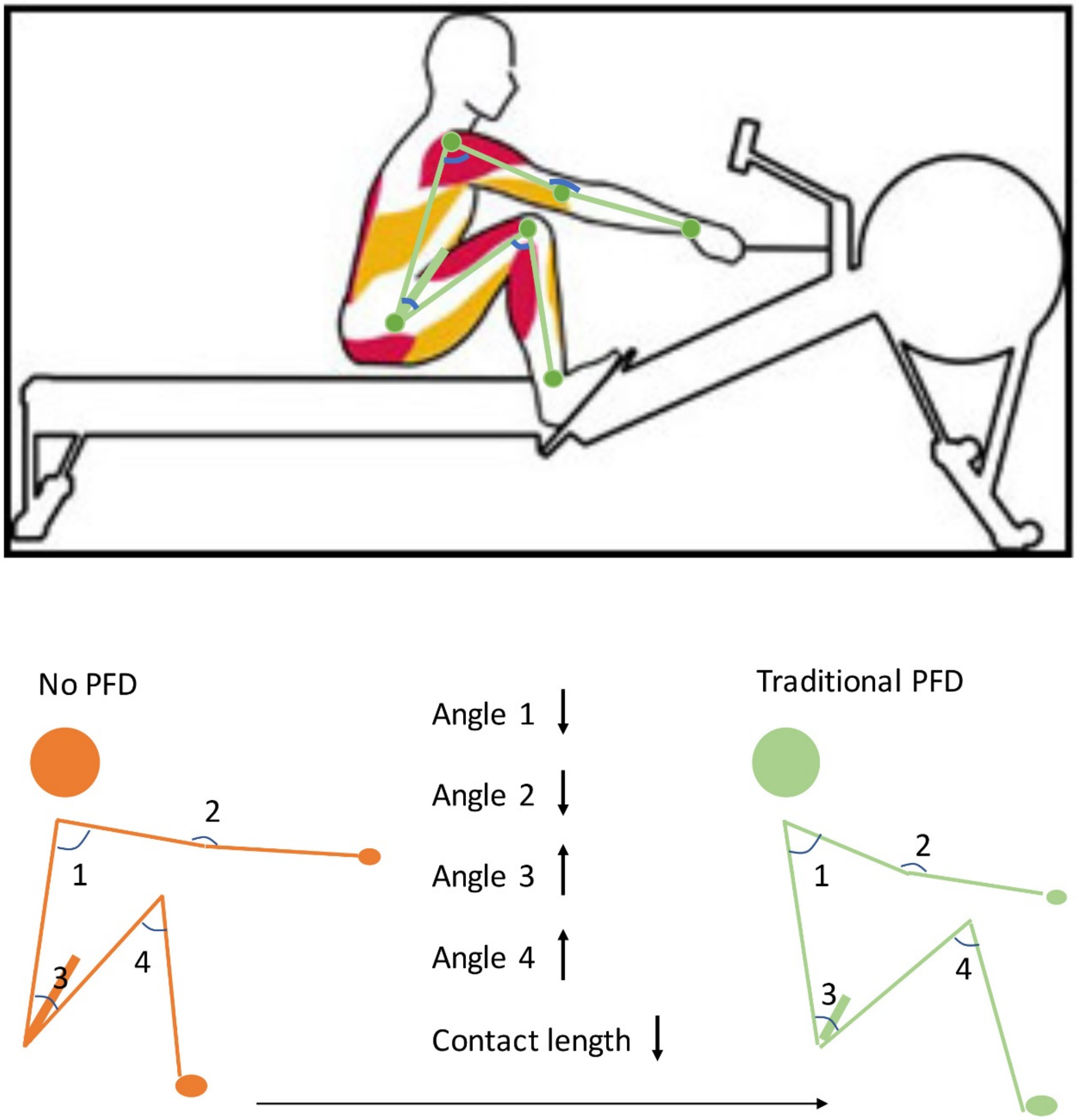


Figure 33 Visual representation of assumptions for catch position

As shown in Figure 33., angle 1,2,3, and 4 represent angles between arm and torso, upper arm and forearm, torso and thigh, and between thigh and calf correspondingly. Hypothetically, it is expected that the range of motion would be influenced by the traditional type II PFD used in the pre-test. Firstly, it is likely that the rower cannot move their upper body as forward as possible due to the foam applied between torso and thigh. As a result, angle 3 (torso and thigh) would increase accordingly while angle 1 (arm and torso) decreases. Although there might be no direct influence applied onto forearm and calf, it is expected that angle 2 (upper arm and forearm) would slightly reduce and angle 4 (thigh and calf) may slightly increase when take into the consideration of the whole-body balance.

The thicker line between torso and thigh in Figure 33 shows the contact length between thigh and torso. Due to the increasing of angle 3, it is reasonable to predict that contact length between thigh and torso would reduce as a result.

Results

According to the boxplot graphs for all pairs of measurements, it is reasonable to believe that wearing traditional type II PFD affects participants' range of movement. The joint angle data presented in Table 17 compares the range of movements for 7 rowers with and without PFD in the catch position.

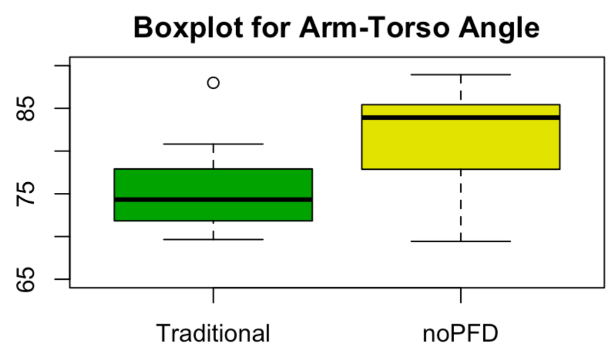
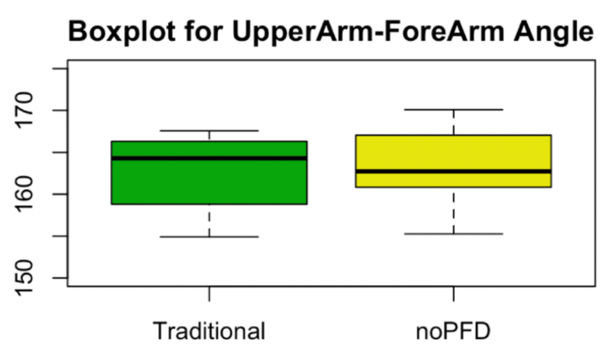
The difference in angle 1 (Table 17. (a)) and angle 3 (Table 17. (c)) between two conditions are significant, and the data trends confirmed assumptions for these two angles. On average, wearing the traditional PFD decrease angle 1 by 4.46 degree (6%) and increase angle 3 by 3.39 degree (8.4%). The relative larger value of angle 1 and smaller value of angle 3 in the PFD condition seem to be caused by the thick front panel of the traditional PFD.

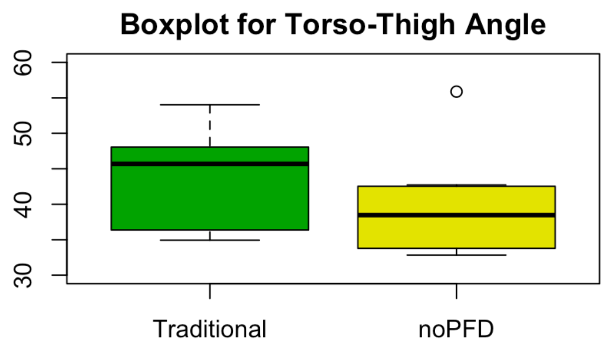
For angle 2 and 4, the changes happen on a relatively small scale, but the data trends still fit the assumption. The mean value of angle 2 in PFD condition is slightly lower (1.07 degree, which is decreased by 0.65%) while angle 4 in PFD condition is slightly larger (1.57 degree, increased by 2.6%). Such changes are the results of whole-body balance adjustment.

Meanwhile, the contact length of thigh and torso has been significantly reduced by the traditional PFD (Table 18, which is 17% lower in the PFD condition compared to the control condition. This significant reduction is also due to the restriction from the front panel.

In conclusion, through the comparison of 5 measurements with and without the traditional PFD, assumptions for the catch position have been confirmed.

Table 17 Comparison of joints angle in Catch position

<table>
<tr><th>Joint angle in Catch position</th><th colspan="4">Statistics and Graph</th></tr>
<tr><td rowspan="4">(a) Angle between Arm and Torso (Angle 1) (Degree)</td><td>Condition</td><td>Mean</td><td>STD</td><td>Difference</td></tr>
<tr><td>Traditional PFD</td><td>76.67</td><td>6.40</td><td rowspan="2">4.46</td></tr>
<tr><td>No PFD</td><td>81.13</td><td>7.07</td></tr>
<tr><td colspan="4">
</td></tr>
<tr><td rowspan="4">(b) Angle between Upper-Arm and Forearm (Angle 2) (Degree)</td><td>Condition</td><td>Mean</td><td>STD</td><td>Difference</td></tr>
<tr><td>Traditional PFD</td><td>163.69</td><td>4.94</td><td rowspan="2">1.07</td></tr>
<tr><td>No PFD</td><td>164.76</td><td>5.19</td></tr>
<tr><td colspan="4">
</td></tr>
</table>

	Condition	Mean	STD	Difference
(c) Angle between Torso and Thigh (Angle 3) (Degree)	Traditional PFD	42.77	7.50	3.39
	No PFD	40.22	8.12	
				

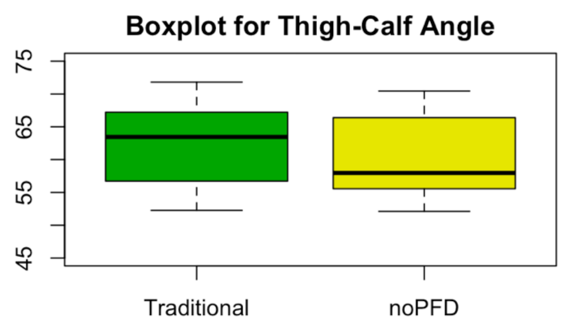
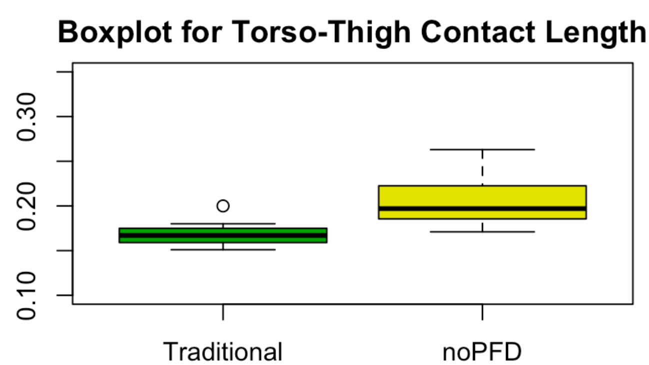
	Condition	Mean	STD	Difference
(d) Angle between Thigh and Calf (Angle 4) (Degree)	Traditional PFD	61.29	7.14	1.57
	No PFD	59.90	7.15	
				

Table 18 Comparison of contact length

	Condition	Mean	STD	Difference
Contact length of Thigh and Torso (m)	Traditional PFD	0.17	0.02	0.0373
	No PFD	0.21	0.03	
				

Assumptions for finish position

For the same rationale as the catch, assumptions for finish position proposed as demonstrated in Figure 34.

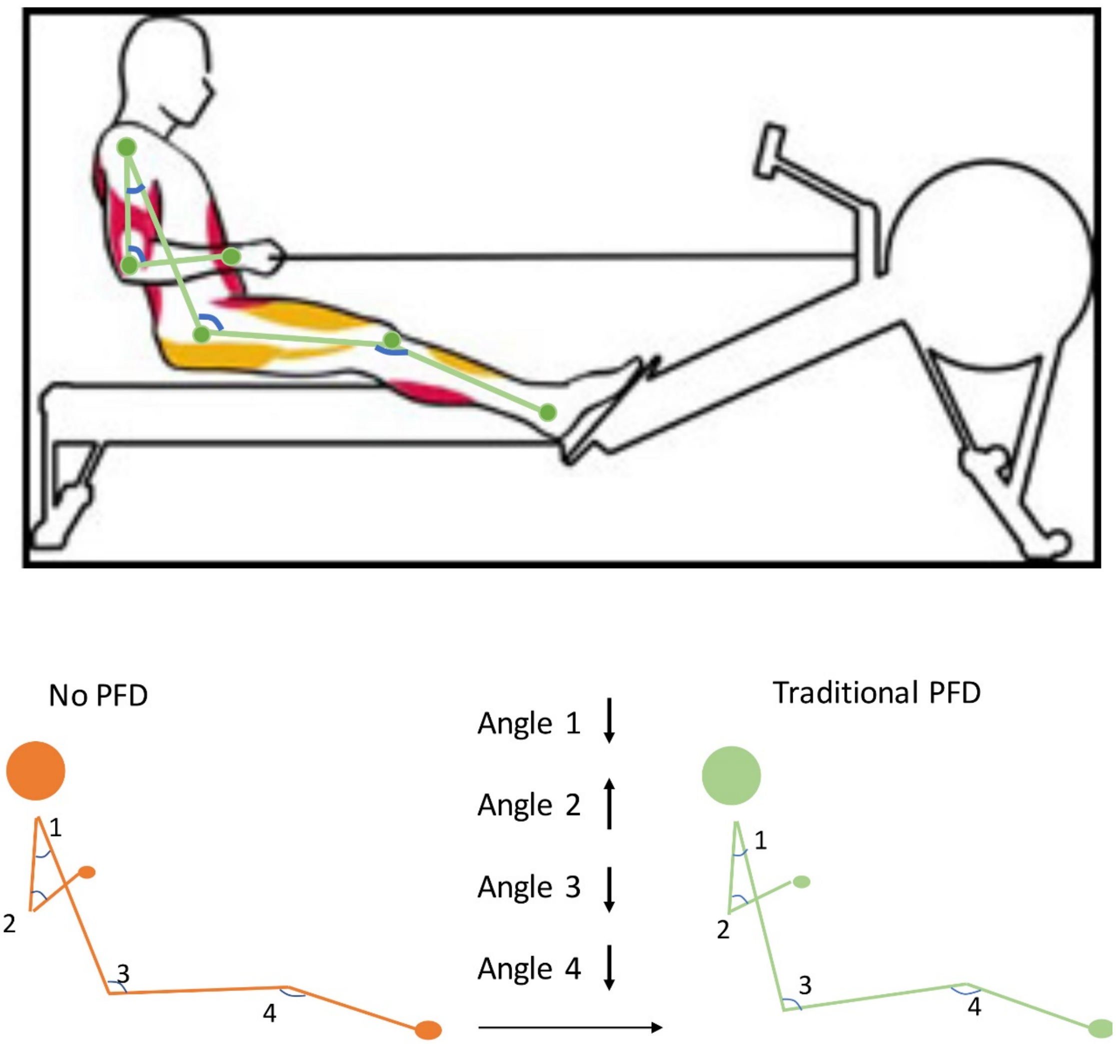


Figure 34 Visually represents assumptions for finish position.

Angle 1,2,3, and 4 represent angles between arm and torso, upper arm and forearm, torso and thigh, and between thigh and calf correspondingly as shown in Figure 34. Hypothetically, with the traditional type II PFD, with the foam placed on the front chest, it is likely that the rower cannot pull their hands as close to their torso as possible. Henceforth, angle 1 and angle 3 would decrease accordingly. Although there is no direct influence applied onto forearm and calf, considering of the whole-body balance, it is expected that angle 2 would increase because of the decrease of angle 1 and 3 to achieve body balance. Similarly, footsteps may not be able to let rowers push their body away as far as possible, which seems to cause angle 4 to be decreased.

Results

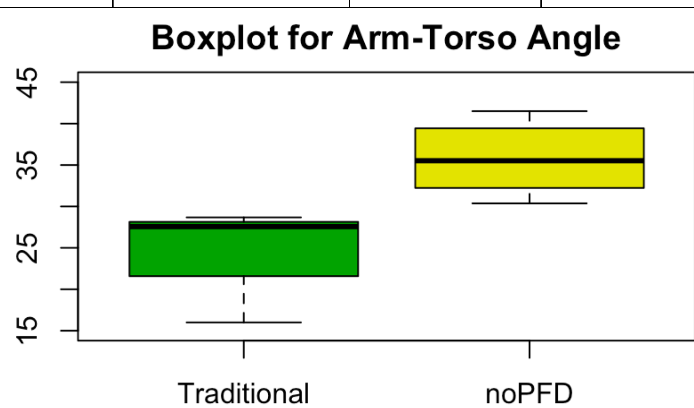
According to the boxplot graphs for all pairs of measurements, it is reasonable to believe that wearing traditional type II PFD as used in these tests affects participants' range of movement at finish position. The joint angle data is presented in Table 19.

The difference in angle 1 (Table 19. (a)) and angle 3 (Table 19. (c)) between two conditions are significant, and the data trends confirm the assumptions for these two angles. Angle 1 decreased by 31.2% from control condition to PFD condition, which is likely to be due to the front panel that prevents the hands from reaching the chest area. For angle 3, although the difference (4.9 degrees, which accounts for 4% changes) seems to be trivial, the datasets for the two conditions apparently are within different ranges. Change in angle 3 is likely to be the result of coordination of the body movements when participants' hands cannot pull as close to their chest as possible. As expected, angle 2 in PFD condition is slightly larger than in control condition, which probably because of the coordination between upper arm and forearm.

However, the difference in angle 4 is marginal. The data scopes for two conditions are very similar and their mean values are close to each other, which indicates no significant difference exists. This is reasonable result at where there is no contact with the PFD.

In conclusion, through the comparison of 4 measurements in finish position with and without traditional PFD, assumptions of joint angle changes for finish position have been partially confirmed. The data collected concludes convincingly that wearing traditional PFD reduces values of angle 1 and angle 3, while slightly increases the value of angle 2. Angle 4 seems not to be significantly affected by the PFD based on data obtained from the current sample.

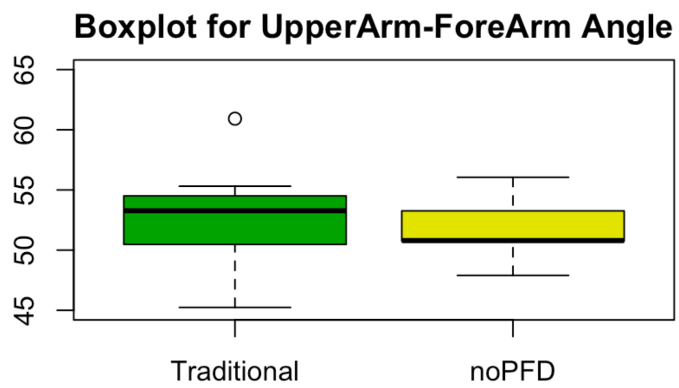
Table 19 Comparison of joint angle in Finish position

<table>
<tr><th>Joint angle in Finish Position</th><th colspan="4">Statistics and Graphs</th></tr>
<tr><td rowspan="4">(a) Angle between Arm and Torso (Angle 1) (Degree(angle))</td><td>Condition</td><td>Mean</td><td>STD</td><td>Difference</td></tr>
<tr><td>Traditional PFD</td><td>24.94</td><td>5.44</td><td rowspan="2">11.29</td></tr>
<tr><td>No PFD</td><td>36.21</td><td>4.57</td></tr>
<tr><td colspan="4">


</td></tr>
</table>

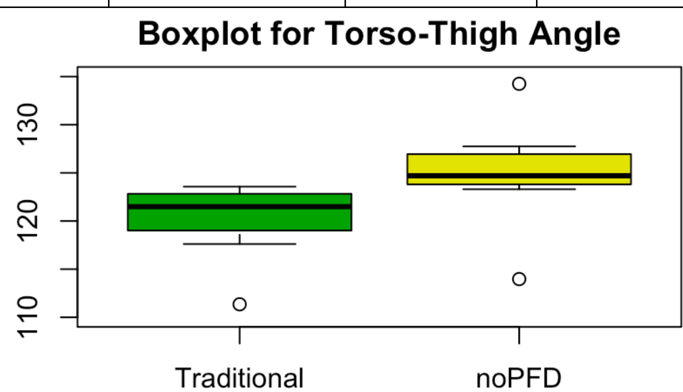
(b) Angle between Upper-Arm and Forearm (Angle 2) (Degree(angle))

Condition	Mean	STD	Difference
Traditional PFD	52.62	4.38	0.947
No PFD	52.00	3.52	



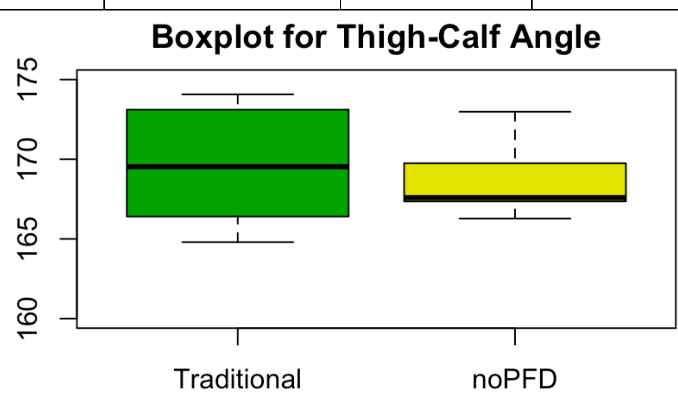
(c) Angle between Torso and Thigh (Angle 3) (Degree(angle))

Condition	Mean	STD	Difference
Traditional PFD	119.77	4.79	4.9
No PFD	124.71	5.21	



(d) Angle between Thigh and Calf (Angle 4) (Degree(angle))

Condition	Mean	STD	Difference
Traditional PFD	170.44	3.44	0.91
No PFD	168.91	2.63	

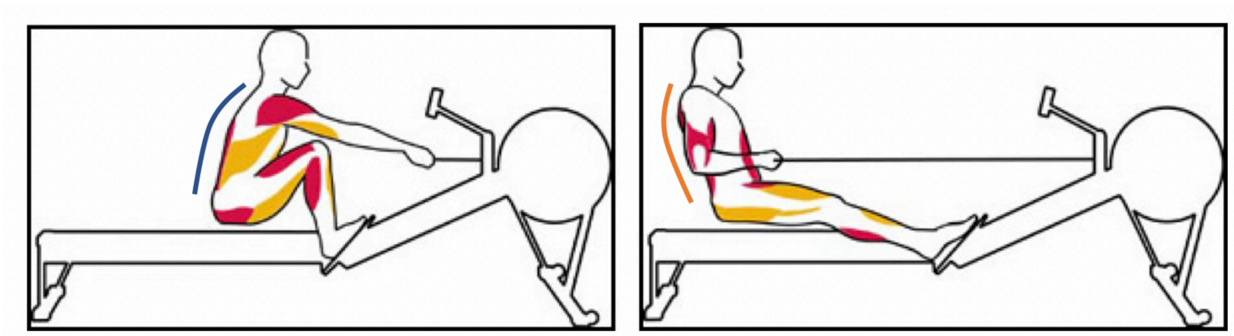


4.1.2 Dynamic anthropometric comparison

Back length

Back length measurements in catch and finish positions have been visualized in Figure 35, and the comparison results presented in Table 20.

Back length was greater in finish position than in catch position by about 0.01 meter on average, which was consistent in all participants. Since the difference is very finite, and the vertical shift of the garment can make up for the back-length change, it was determined not to have additional stretch aids on the back in the prototyping process.

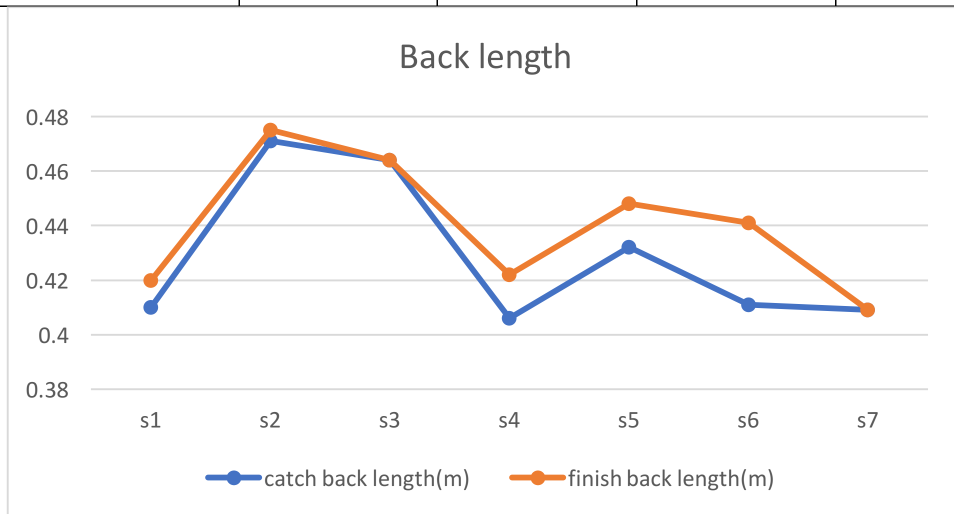


(a) (b)

Figure 35 Visual demonstration of back-length change in catch (a) and finish (b) positions

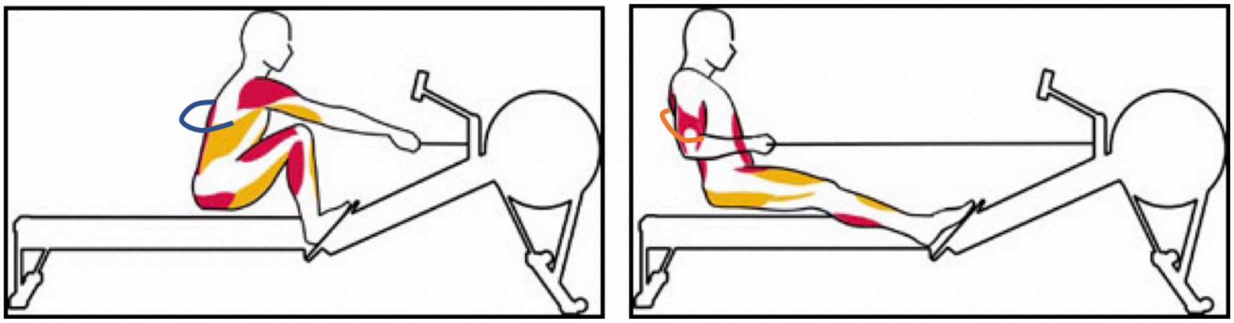
Table 20 Back length comparison in catch and finish positions

	Paired-T Test Statistics and Graphs				
	Position	Mean	STD	Estimated Difference	Paired-T Test P-value
Back length (m)	Catch	0.43	0.03	0.01	0.038*
	Finish	0.45	0.02		



Half chest circumference on the back side (HCB)

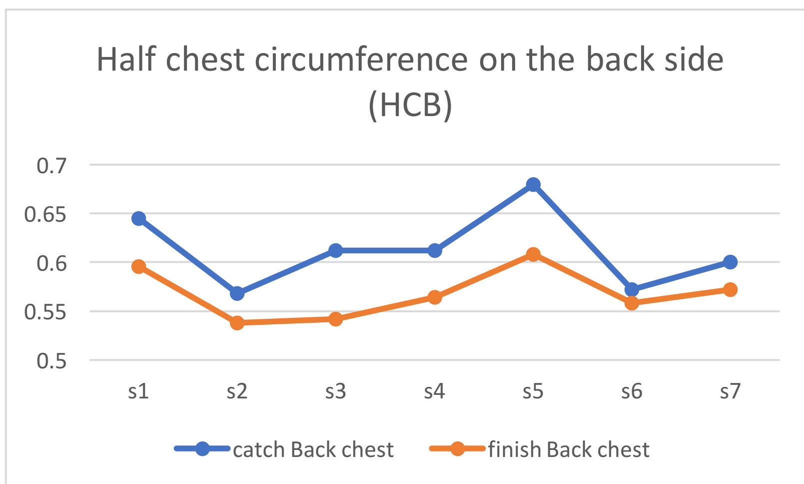
HCB in catch and finish positions have been visualized in Figure 36, and the comparison results presented in Table 21. HCB was consistently greater in catch position than in finish position by about 0.044 meter on average. Since the difference is relatively obvious and the chest enlargement can only be accommodated by the radial stretch of the garment, extra stretch aids are needed on horizontal direction of the garment. As a result, two side panels made of power mesh materials were added for the prototype to ensure enough stretchability.



(a) (b)

Figure 36. Visual demonstration of HCB in catch and finish positions

Table 21 HCB circumference comparison in catch and finish positions

	Paired-T Test Statistics and Graphs				
	Position	Mean	STD	Estimated Difference	Paired-T Test P-value
	Catch	0.62	0.04	0.044	0.0017**
	Finish	0.57	0.03		
HCB (m)					

Note: ** represents 0.01 significance level

Half-shoulder Length

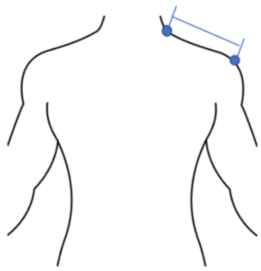
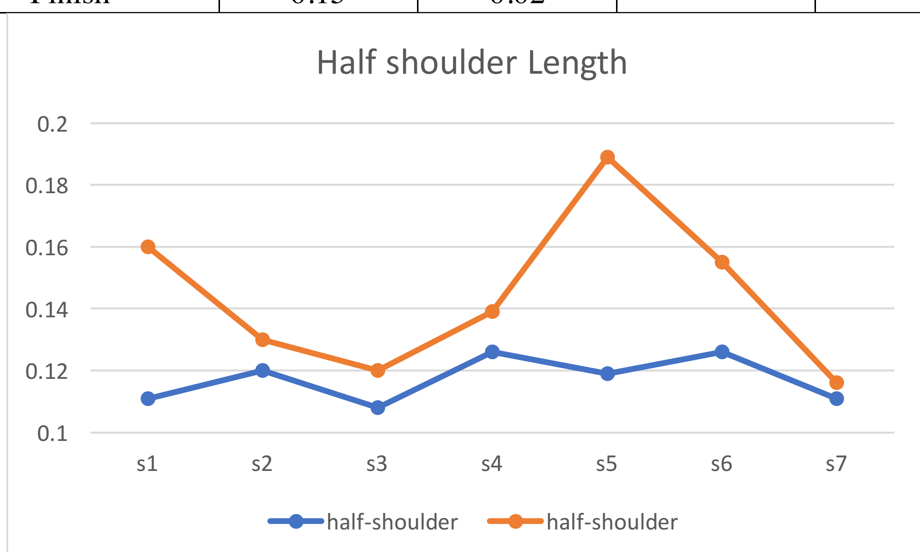


Figure 37 Half-shoulder length

As shown in Table 22., half-shoulder length is significantly larger, 25% increase, in finish position than in catch position. Such change suggests vigorous shrinking and expanding activities at shoulder area, which might cause rubbing against the shoulder straps. Thus, an appropriate shoulder strap width (6cm) were applied to the prototype based on the half-shoulder length data.

Table 22 Half-shoulder length in catch and finish positions

	Paired-T Test Statistics and Graphs				
	Position	Mean	STD	Estimated Difference	Paired-T Test P-value
	Catch	0.12	0.01	0.027	0.02632*
	Finish	0.15	0.02		
Half-shoulder length (m)					

4.1.3 Hands movement range

For each participant, the distances between their hand and chest line at touching point and leaving point were recorded for data analysis.

As shown in Table 23, averagely, participants begin to start to contact with their chest area from the level that 4.39±1.96 cm lower than chest line, and the handle movement range is 4.77±2.22. According to data from the side view, hands movement range is observed to be a bit wider (5±1.35 cm) and closer (0.25±1.66 cm) to the chest line. In Figure 38., data was transferred and the individual and average hands movement range have been visually demonstrated on the body figure.

Table 23 Results of contact area and handle movement range

	Subject No.	1	2	3	4	5	6	7	Mean	SD
Front-view	Distance from chest line to Touching point (cm)	5.8	3.1	3.8	5.2	0.8	6.4	5.6	4.39	1.96
	handle movement range near chest(cm)	4.1	5.2	5.3	4	9.2	3.4	2.2	4.77	2.22
Side-view	Distance from chest line to Touching point(cm)	1	-1	-1.2	0.4	-0.6	3.6	-0.4	0.25	1.66
	hand movement range near chest(cm)	4.9	3.8	3.7	7.4	6.2	4.6	4.4	5	1.35

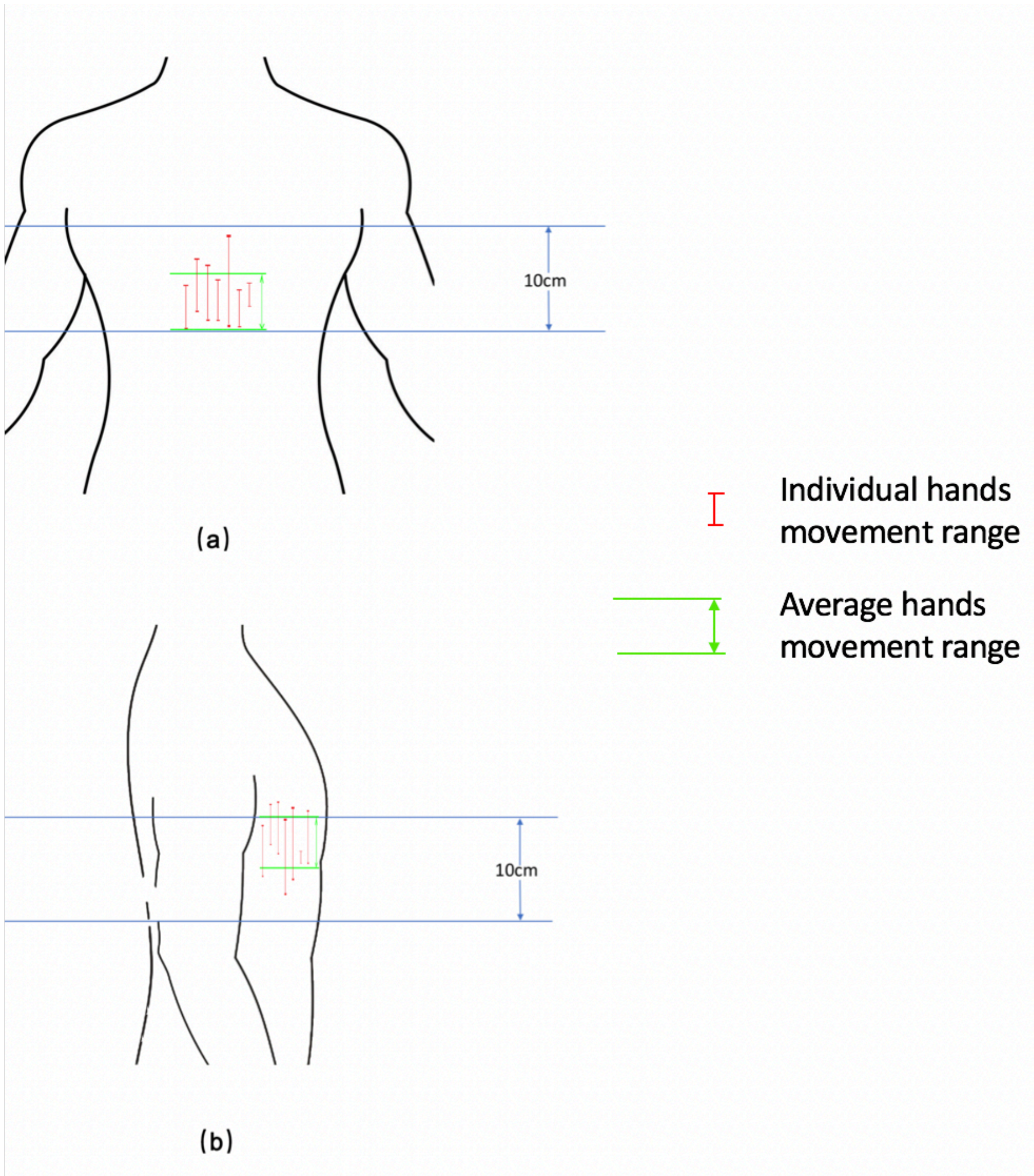


Figure 38 Visual demonstration of Hands Movement Range Data: (a) Front View; (b) Side View

Data from video analysis has been applied to prototyping process as described in Chapter 3. Additionally, since hands are very close to chest line from side view, it is reasonable to make the side panel without foam.

4.1.4 Interview results

Phase I Personal experience

On a scale from -3 (cannot swim at all) to +3 (professional level), where 0 represents the level of one has the ability to pass the Cornell swimming test, participants' average swimming skill rating is 1.07 ±0.6. This result indicates that their self-perceived swimming ability is a bit higher than simply “can swim”. Only subject 2 feels that he is at the level of “can pass” the swimming test, all other people believe they are better than average or are good swimmers.

As for the experience of wearing PFD while rowing, only one rower has such experience, which was wearing an inflatable PFD in Germany, where PFDs are required for rowers in several German states. He is also the only participant from a foreign country, which might indicate the different safety atmosphere between U.S. school rowing teams and the ones in Germany. The reasons other rowers offered for never using PFD can be summarized as: restrictive to their motion, not the culture, or has no worry about accidents.

All participants have cold water experience while no one has experienced accidents in cold weather. The challenging factors, according to their descriptions, can be summarized as the wind (5 responses), water conditions (3 responses), coldness (2 responses), and water splash (1 response). Speaking of the coldness, all participants could feel that the harsh coldness happens on extremities when they are on boat during cold weather.

In cold weather rowing, participants usually wear 3~4 layers on top, which typically includes the base layer, thermal underwear, T-shirt and a waterproof outwear. It is notable that all participants mentioned that they would wear something to prevent rain and water splash, which suggests the need for waterproof function in harsh weather.

As visualized in Figure 39, rowers claimed that while their shoulders and hip joints need most mobility, knees and elbow joints also need enough range of motion for good performance.

Figure 39 Visual demonstration of Mobility Needs in Rowing
Note: Figures from "Concept 2" Official website, retrieved from: http://www.concept2.com

Regarding their fitting preference, all participants indicated that they prefer compression garments since loose cloth would get caught when their hands are approaching towards body.

Besides, interviews have indicated that the most thermal-sensitive and prone-to-sweat areas are the upper back and front chest area.

Phase II Perceptions of the test PFD

In general, participants feel that the traditional PFD is large and very bulky whereas their perceptions of its weight and fit are neutral, results shown in Table 24.

Table 24 Perceptions of Traditional PFD

	Size (-2 too small; 0 neutral; +2 too large)	Weight (-2 very light; 2 too heavy)	Shape front (-2 too narrow; 2 too wide)	Shape profile (-2 too thin; 2 too thick)	Fit (-2 Too tight; 0 neutral; 2 Oversize)
Mean	1.43	0.29	1.29	1.714	0
SD	0.97	1.38	0.95	0.487	0.82

The general complaints and comments for the traditional PFD are visualized in Figure 40., which can be categorized into mobility and tactile comfort issues.

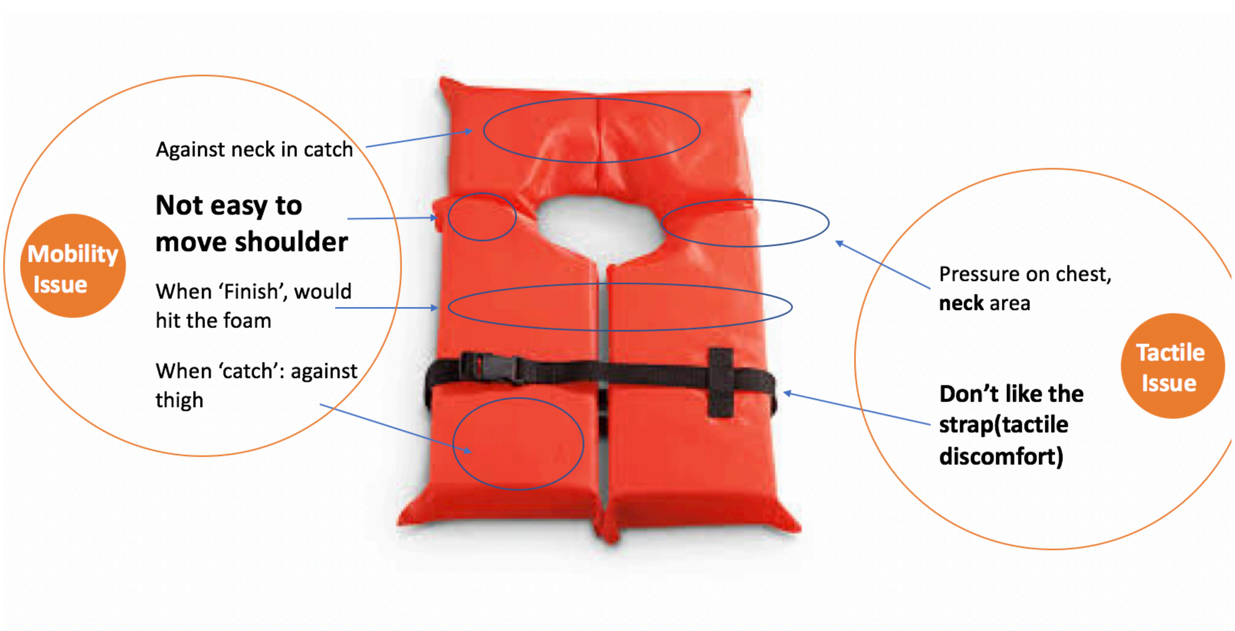


Figure 40 Visual demonstration of comments on Traditional PFD
Note: Bolder and larger font represents higher frequency

Based on participants' suggestions, a life jacket that has light shoulder design, is slim around the chest, flexible and breathable would be the kind of PFD that they prefer. Also, some other design features are frequently mentioned as better choices, including water resistance on the back, no buckle on the central front and the pull-over design.

4.1.5 Discussion

The results of the subjective perceptions obtained by the structured survey confirmed that the use of PFD is not a culture within the sports of rowing, which is mainly due to the restriction on their performance. Although almost all rowers are good swimmers, cold weather rowing is unavoidable for them, in which the accidents rate is always higher compared to in a more stable condition. Rowers do concern about the challenging environmental factors in harsh weather, under this circumstance, they will not only increase the number of top layers they wear but also choose the garment with some additional functions to protect themselves. Henceforth, it is reasonable to believe that there is a possibility to persuade rowers to wear a better designed and more comfortable PFD.

Pre-test also identified the impact of wearing traditional PFD on rowers' motion and performance. Compelling evidences presented through the joint angle data (Table 17 and 19) proved that the traditional type II PFD significantly restricts rowing motion, especially on the hip and shoulder joints (angle 1 and 3). This result is coincident with their subjective feedback that their shoulder and hip joints need the most mobility while rowing (Figure 39.), and their complaints about the traditional PFD (Figure 40.).

The dynamic anthropometric measurements identified related body dimension changes with movement. During rowing, the back length, HCB, and the half-shoulder length are significantly changed because of body movement (Table 20 to 22). These measurements are important references for the prototyping process, which determined the degree and direction of the stretch offered by the prototype, and the shoulder strap width.

In addition, the 'hands movement range' on the front chest area were determined by video analysis (Table 23 and Figure 38). With the intention to leave this area to be unhindered for hands movement, this result is the most significant reference for foam segments placement on the front panel.

To conclude, the pre-test achieved the two purposes presented in the beginning of this subsection:

1) identified needs for improved mobility and overall comfort during rowing.

2) identified the impact of wearing traditional PFD on rowers' motion and performance.

Results and data were applied to the prototyping process for a better designed PFD.

4.2 Post-test results & analysis

Post-test aims at collecting data to evaluate the effectiveness of the new prototype designs (Figure 41.).

Figure 41 Prototype design features

4.2.1 Joint angle comparison

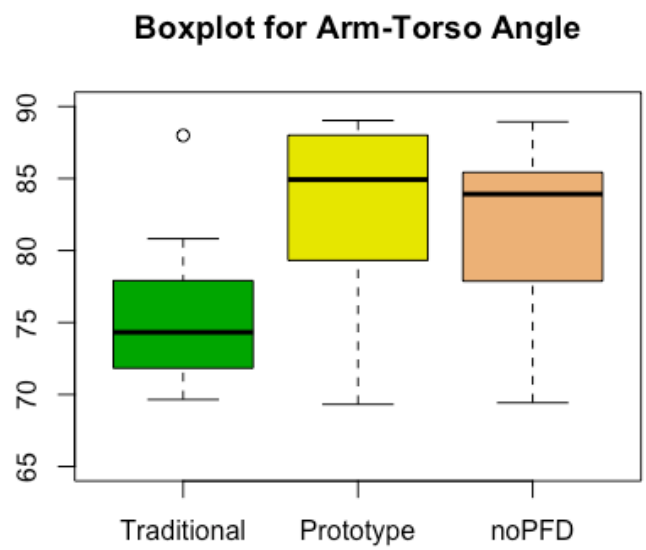
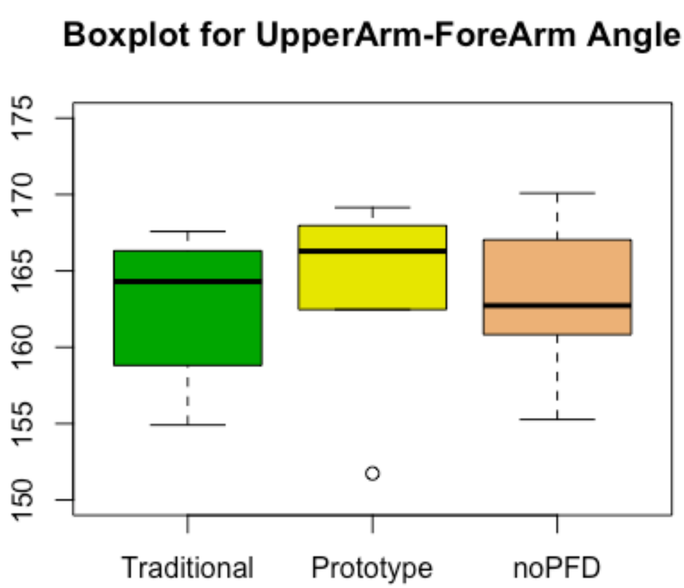
Assumptions

Post-test measures exactly same things as the joint angle comparison in the pre-test. Hypothetically, the prototype has very light or barely any influence on rowers' motion. To be more specific, there's no significant joint angle difference in both catch and finish positions when wearing the prototype and control garments (only the shorts). Besides, when comparing the data trends in three garment conditions (traditional PFD, prototype, no PFD), prototype is expected to show less restriction than traditional PFD on rowing motion.

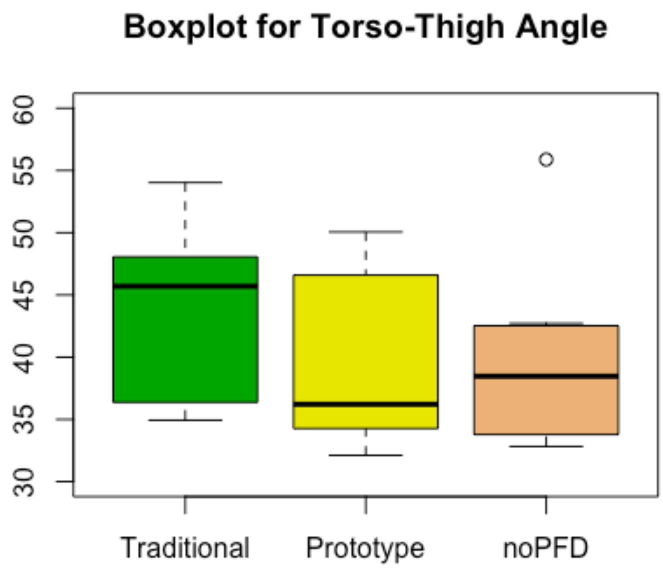
Results

Table 25 and 26 shows the comparison results among three garments conditions in catch position. With attention to the overall comparison shown in the boxplots, some data trends have been observed. For the measurements of angle 1,3 (Table 25 (a) and (c)) and contact length (Table 26), the results are persuasive and can verify the assumption that the data trends in the prototype condition are similar to the control condition and show less restriction on the range of motion than the traditional PFD. Measurements of angle 2 and 4 (Table 25 (b) and (d)) have marginal differences in terms of data trends among three conditions. But for both measurements, it is observed that prototype condition has less influence on joint angles and its data was closer to the control condition. Henceforth, prototype PFD doesn't have an obviously detectable impact on rowing motion like the traditional one does, implying assumptions for catch position have been confirmed.

Table 25 Comparison of joint angle in Catch position

<table>
<tr><th>Joint angle in Catch position</th><th colspan="3">Test statistics and Graphs</th></tr>
<tr><td rowspan="5">(a) Angle between Arm and Torso (Angle 1) (degree)</td><td>Condition</td><td>Mean</td><td>STD</td></tr>
<tr><td>Traditional PFD</td><td>76.67</td><td>6.40</td></tr>
<tr><td>Prototype PFD</td><td>82.59</td><td>7.33</td></tr>
<tr><td>No PFD</td><td>81.13</td><td>7.74</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td rowspan="5">(b) Angle between Upper-Arm and Forearm (Angle 2) (degree)</td><td>Condition</td><td>Mean</td><td>STD</td></tr>
<tr><td>Traditional PFD</td><td>163.69</td><td>4.94</td></tr>
<tr><td>Prototype PFD</td><td>163.99</td><td>6.42</td></tr>
<tr><td>No PFD</td><td>164.76</td><td>4.11</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td></td><td>Condition</td><td>Mean</td><td>STD</td></tr>
</table>

(c) Angle between Torso and Thigh (Angle 3) (degree)	Traditional PFD	42.77	7.50
	Prototype PFD	39.24	7.29
	No PFD	40.22	8.87



(d) Angle between Thigh and Calf (Angle 4) (degree)	Condition	Mean	STD
	Traditional PFD	61.29	7.14
	Prototype PFD	59.00	6.35
	No PFD	59.90	7.53

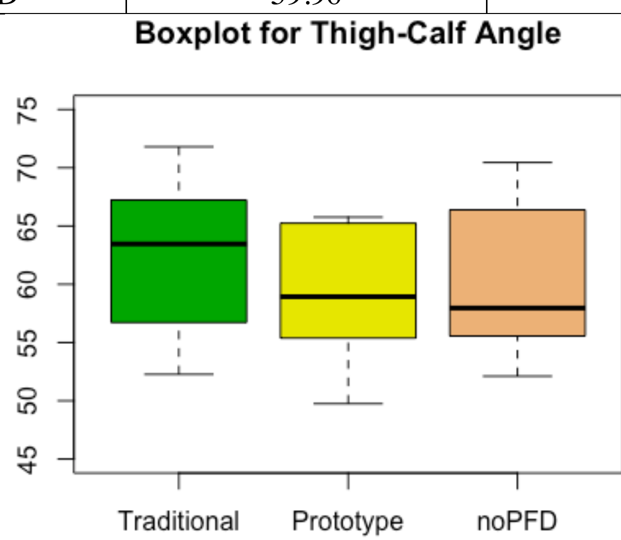


Table 26 Comparison of contact length in Catch position

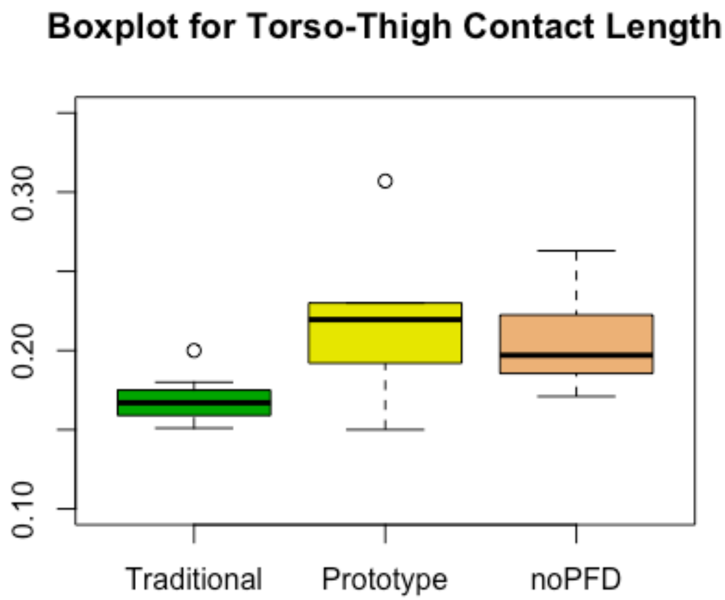
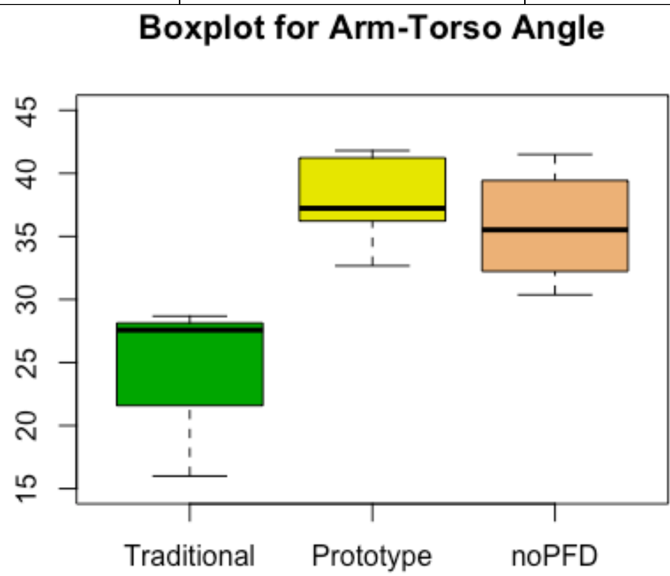
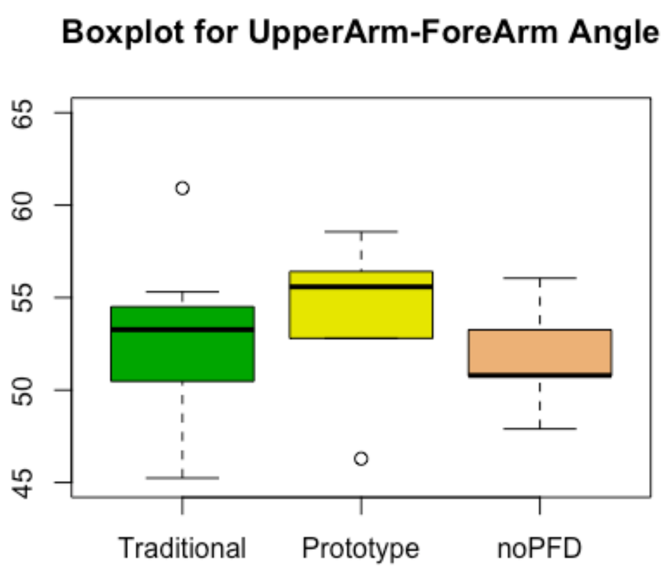
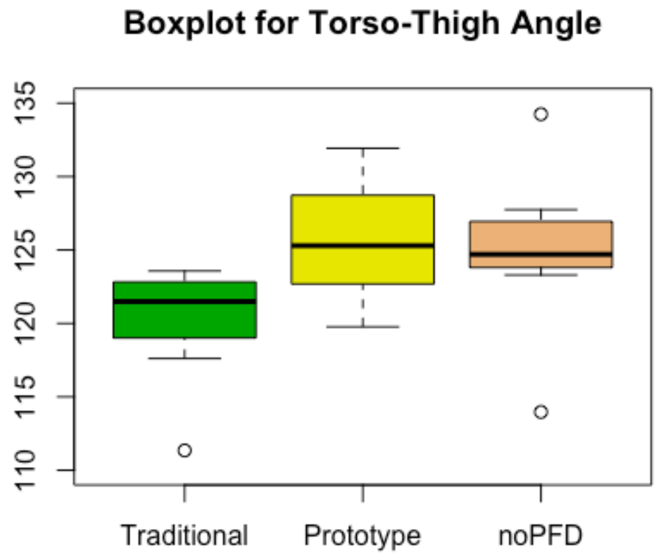
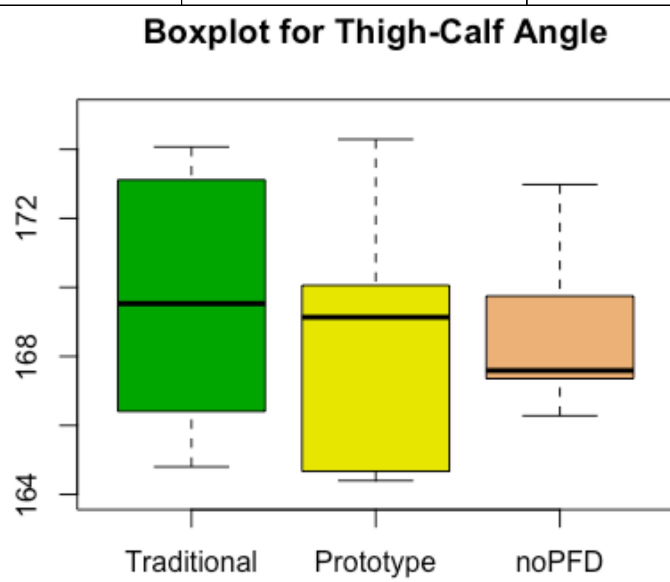
<table>
<tr><td rowspan="5">Contact length of Thigh and Torso (m)</td><td>Condition</td><td>Mean</td><td>STD</td></tr>
<tr><td>Traditional PFD</td><td>0.17</td><td>0.02</td></tr>
<tr><td>Prototype PFD</td><td>0.21</td><td>0.07</td></tr>
<tr><td>No PFD</td><td>0.21</td><td>0.04</td></tr>
<tr><td colspan="3">
</td></tr>
</table>

Table 27 shows the comparison results for finish position. Angle 1 and 3 (Table 27 (a) and (c)) show obviously different data trends on the traditional condition compared to the other two conditions, which proves the prototype to be less influential on shoulder and abdomen area. Boxplots for angle 2 and 4 (Table 27 (b) and (d)) did not give informative evidence to prove the difference among three garment conditions.

As a result, the prototype PFD doesn't have an obviously detectable impact on rowing motion like the traditional one does on angle 1 and 3, implying the assumptions for the finish position have been partially confirmed.

Table 27 Comparison of joint angle in Finish position

<table>
<tr><th>Joint angle in Finish Position</th><th colspan="3">Statistics and Graphs</th></tr>
<tr><td rowspan="5">(a) Angle between Arm and Torso (Angle 1) (Degree)</td><td>Condition</td><td>Mean</td><td>STD</td></tr>
<tr><td>Traditional PFD</td><td>24.94</td><td>5.44</td></tr>
<tr><td>Prototype PFD</td><td>37.73</td><td>3.38</td></tr>
<tr><td>No PFD</td><td>36.21</td><td>4.84</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td rowspan="5">(b) Angle between Upper-Arm and Forearm (Angle 2) (Unit: angle (degree))</td><td>Condition</td><td>Mean</td><td>STD</td></tr>
<tr><td>Traditional PFD</td><td>52.62</td><td>4.38</td></tr>
<tr><td>Prototype PFD</td><td>54.21</td><td>5.33</td></tr>
<tr><td>No PFD</td><td>52.00</td><td>4.30</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td rowspan="2"></td><td>Condition</td><td>Mean</td><td>STD</td></tr>
<tr><td>Traditional PFD</td><td>119.77</td><td>4.79</td></tr>
</table>

<table>
<tr><td></td><td>Prototype PFD</td><td>125.62</td><td>4.31</td></tr>
<tr><td></td><td>No PFD</td><td>124.71</td><td>6.60</td></tr>
<tr><td>(c) Angle between Torso and Thigh (Angle 3) (Unit: angle (degree))</td><td colspan="3">
</td></tr>
<tr><td rowspan="5">(d) Angle between Thigh and Calf (Angle 4) (Unit: angle (degree))</td><td>Condition</td><td>Mean</td><td>STD</td></tr>
<tr><td>Traditional PFD</td><td>170.44</td><td>3.44</td></tr>
<tr><td>Prototype PFD</td><td>168.62</td><td>3.70</td></tr>
<tr><td>No PFD</td><td>168.91</td><td>2.62</td></tr>
<tr><td colspan="3">
</td></tr>
</table>

4.2.2 Subjective comparison

As shown in Table 28, the traditional life jacket needs less time for donning and doffing because of its simple design and could be buckled with only one single step. The ratings of it in terms of donning and doffing process and overall ease of use are also more positive than the ratings of prototype PFD. They claimed that the pull-over design is the reason they feel a bit harder to put on. But speaking of the completely open zipper, they believe it may need even more time and patience to align it. Even though the overall convenience of the prototype seems to be less than the traditional PFD, all ratings for the prototype is above or equal to neutral, and participants indicate that the wearing process is entirely acceptable for them.

Table 28 Donning and Doffing time and rating

	Donning time(s)		Donning rating		Doffing Time(s)		Doffing Rating		Overall ease of use	
	T	P	T	P	T	P	T	P	T	P
Mean	13.60	15.39	1.00	0.00	4.55	7.41	2.17	0.33	0.83	0.17
SD	10.77	2.89	1.79	1.79	1.26	1.45	1.17	1.51	2.04	1.33

Note: T- Traditional PFD, P-Newly developed Prototype PFD

The ideal life jacket should be fit, light with an unobstructed shape. Shown in Table 29., participants gave much more positive feedback on the size and shape of the prototype PFD. Although the weight and fit perceptions for two life jackets are both positive and similar from one to the other, the prototype receives slightly better reviews. One participant even addressed that the tightness of the prototype is tight in a good way. The overall rating suggests the prototype is much better (average score is 2.5, in which 0 represents two of them are the same) than the traditional one based on their experience of wearing and rowing with it. If the seven scales are taken as a complete scroll bar, 0 represents 50% and 2.5 represents 91.7%. This indicates the prototype increased the overall perception by 83.3% (91.7%-50%)/50% = 83.3%).

Table 29 Perceptions Comparison

	Size (-2 too small; 0 neutral; +2 too large)		Weight (-2 very light; 2 too heavy)		Shape-front (-2 too narrow; 2 too wide)		Shape-profile (-2 too thin; 2 too thick)		Fit (-2 Too tight; 0 neutral; 2 Oversize)		Comparison (-3 Prototype is much worse than Traditional one; 3 Prototype is much better than Traditional one)
	T	P	T	P	T	P	T	P	T	P	
Mean	1.33	0.00	-0.17	-0.33	2.00	0.33	1.67	0.67	0.20	-0.17	2.50
SD	0.82	0.00	0.98	1.03	0.00	0.82	0.82	0.52	0.84	0.41	0.55

Note: T- Traditional PFD, P-Newly developed Prototype PFD

Notably, mobility rating largely improved from almost 'extremely restricted' to very near to 'like no PFD' as shown in Table 30.

Table 30 Mobility Rating

Mobility (-3 extremely restricted; 0 like no PFD; +3 much better than without PFD)		
PFD	T	P
Mean	-2.67	-0.33
SD	0.52	1.17

Tactile comfort rating for prototype PFD is also much better than traditional one (Table 31). There are almost no negative comments on the tactile sensation of the prototype. The only issue is that the lower abdomen foam applied some pressure in catch position.

Table 31 Tactile Rating

Tactile comfort (-3 extremely uncomfortable; 3 extremely comfortable)		
PFD	T	P
Mean	-1.67	1.00
SD	0.82	1.41

The results of the last open-ended question were summarized in Figure 42.

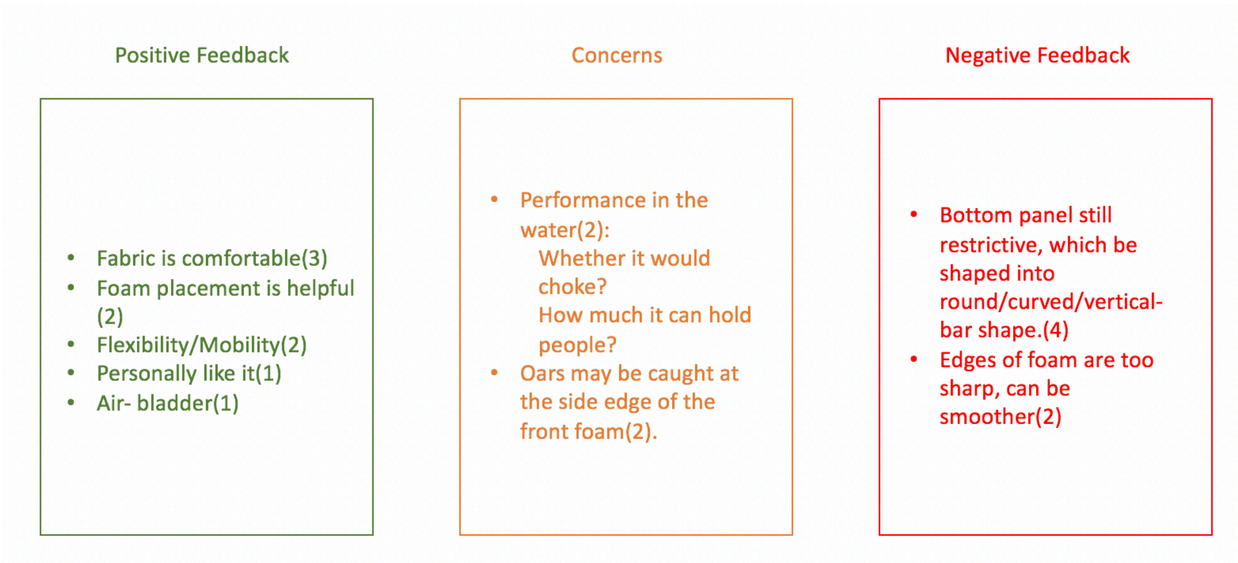


Figure 42 Summary of Open-ended suggestions
Note: Number for each point indicates its frequency.

4.2.3 Ideas for further improvement of PFD design for rowers

Regarding the concerns and negative feedbacks from participants, 2 more foam placement ideas have been proposed after further communication with participants (Figure 43 and 44). Left one is based on their concern that the side foam edges may hinder the oars in the relatively unstable on-water rowing. Right one basically responses to their suggestions to make the transition steps smoother.

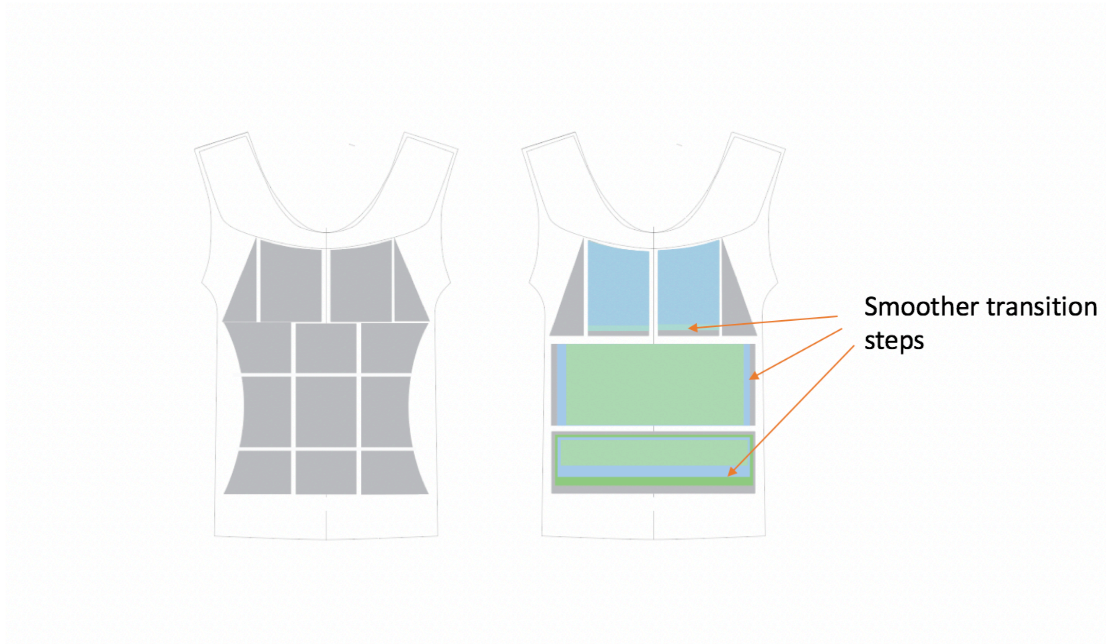


Figure 43 Foam placement ideas (different colors indicate different foam layers)

Figure 44 Foam placement ideas

4.2.4 Flotation Test

Regarding the concerns proposed by the head coach and rowers, a flotation test for the newly developed PFD was conducted in Cornell swimming pool under the supervision by the safe guards. The subject is the researcher herself. And it confirmed the prototype can hold people in a face up position while support the head and parts of chest to be above the water (Figure 45).

Figure 45 Flotation test for the prototype

4.2.5 Discussion

Post-test compared participants' range of movement when wearing the traditional PFD, the prototype PFD and the control garment only. It proved that the prototype PFD doesn't have an obviously detectable impact on rowing motion like the traditional one does. As a matter of fact, this result is coincident with their feedback that their subjective ratings for mobility increased by 2.34 (7 scales) from almost extremely restricted to very close to 'like no PFD'. With the slight restriction on abdomen area reported by participants, the prototype significantly improved mobility with its less obstructive design, flexible segments, stretchable fabric, and tight-fit features. The perceptions of size and shape improved a lot from traditional PFD to the prototype and the overall comparison rating indicates the perception increased by 83%. The tactile and thermal comfort of the prototype also significantly increased and participants have very positive feedback on the sensation, elasticity, and the breathability of the fabric.

To conclude, the post-test achieved the purpose presented in the beginning of this subsection to evaluate the effectiveness of the new prototype design. Based on the evaluation, 2 more foam placement design have been proposed as a solution to solve the negative feedback. As a result, it is confirmed that the prototype achieved better mobility and overall comfort in the sport of rowing.

In addition, further improvement solutions were proposed and preliminary flotation test was conducted to respond the concerns and feedbacks from the post-test.

CHAPTER 5

CONCLUSIONS

This study achieved the goals presented in the 1st chapter, which include:

1) identifying needs for improved mobility and overall comfort during rowing.

2) identifying the impact of wearing traditional PFDs on rowers' motion and performance.

3) developing new PFD prototype with unobstructed appearance, improved comfort, and minimized impact on rower's performance

4) evaluating the effectiveness of the new prototype designs.

Findings of this study was summarized below.

Firstly, quantitative data from the pre-test concluded that the traditional Type II PFD (the PFD used in this study as the traditional PFD, see Figure 14) significantly restricted rowing motion, especially on the hip and shoulder joints in both of the catch and finish positions. The dynamic anthropometric measurements identified related dimensional changes of rowers' body in motion, providing valuable reference for the prototype design. With the intention to leave hands motion to be unhindered, the unique measurement 'hands movement range' was developed in this study as the most significant reference for foam placement design on the front panel. Meanwhile, the qualitative data obtained from the pre-test confirmed that the nonuse of PFD was the prevailing culture among rowing teams and offered more informative design inspirations for the prototype.

Secondly, the prototyping process, accompanied by trials and errors, applied the pre-test data to the new prototype design. This process explored a new method to develop a better PFD for specific activities by applying knowledge from multiple disciplines.

Thirdly, with the quantitative and qualitative data, post-test evaluated the effectiveness of the newly developed prototype and confirmed the improved mobility and overall comfort provided by the prototype. In addition, preliminary flotation test was conducted to confirm the safety concerns. Further improvement solutions were also proposed based on the evaluation results.

Based on the literature reviews and interviews in this study, it is apparent that the current safety situation existing in the sport of rowing needs to be improved. Although the culture of not wearing PFD may not be altered right away, it is necessary to start to improve the situation among amateurs, beginners, single practitioners, teenagers, and elder rowers. Especially after the most recent tragedy happened to Mohammed Ramzan (2017), who was a nineteen-year-old male freshman rowing with Northwestern University's (club) crew team (Chiu, 2017), the regulation regarding the use of PFD should be reconsidered for rowing team. To promote such changes, a better-engineered life jacket can serve as a catalyst and motivate the PFD usage among rowers. The development of such a 'rower-friendly' life jacket with scientific data and methods in this study is a critical step for rowing safety. Findings of this study also demonstrated possibility of improving PFD optimized for rowers based on careful consideration of human factors, and understanding of rowers' motion and key performance features.

This study had a few limitations.

There was five months' gap between the pre- and post-test due to necessary time to develop prototypes. It is possible that participants' rowing pattern might have changed due to their constant training, change of body strength, and influence from teammates. All these changes could potentially affect their range of motion during post-test. Subjects' body dimension may also have changed during this period.

Because of the relatively small sample size, statistical analysis was limited. In addition, for maximum control of experiment environment, safety issue and efficient experiment control, pre-test and post-test were performed in indoor rowing practice facility, where rowers could have different perceptions of wearing the test PFD and prototype compared to rowing outdoor.

Finally, because of the safety concern, flotation test was only performed by the researcher in a swimming pool with presence of safeguard.

Considering the limitations, the future studies with a larger sample size, outdoor on water field test can verify the finding of this study and provide more meaningful and practical implications based on the rowers' on-water feeling and real-world performance. Ergometer score and measurements of oxygen uptake can also be applied to the study as a metabolism index reference. Floatation test with more rower participants with varying body figures and fat proportion can also provide more reliable and rigorous data to evaluate performance of PFD in accidents.

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APPENDIX 1 PRE-TEST QUESTIONNAIRE

Phase1: Questionnaire about personal experience

Personal experience

1. Your height, weight, top size you usually wear? Chest measurements (measured by tape)?

2. How long you have been rowing?

3. How do you rate your swimming skills?

-3 -2 -1 0 1 2 3

-3 cannot swim at all
-2 can barely keep head above the water
-1 could swim, but not skilled
0 could pass the swim test
+1 better than average
+2 skilled swimmer
+3 professional level

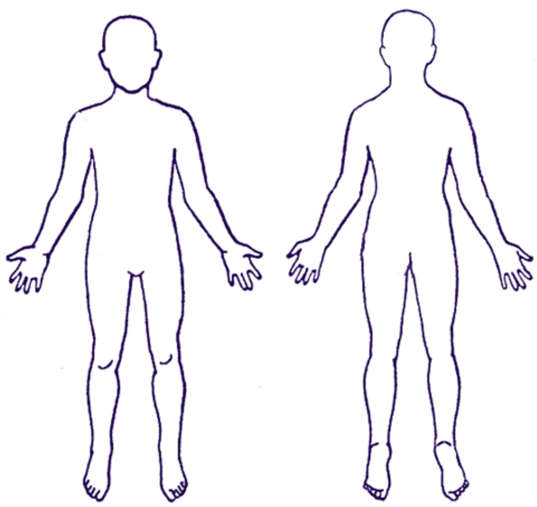
3.Have you ever wore PFDs during training sessions/recreational rowing/single rowing or any other time in your past rowing experience?

If you have, what kind of PFD did you wear?
□Inherent buoyancy PFD
□Inflatable PFD
□Hybrid type
□Others(Please specify)

If have **not,** why? Were there other types of protection going on(like chasing boat)?

4. Have you ever rowed during very cold weather (under 50 degree)? Describe the experience, and talk about the challenging environmental factors based on your experience.

If you did, could you please indicate which part on your body feels cold during rowing (indicate by sequence: most cold, secondary….)



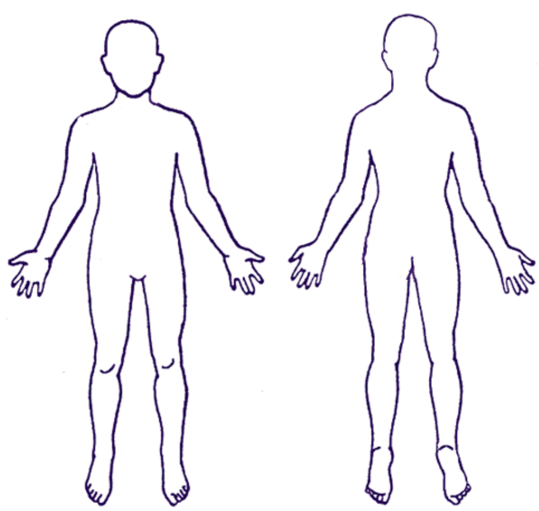
Please also check what garments you would wear when rowing in the cold weather?
Top:
□Base layer(top) □Thermal Underwear □T-shirt □Sweater □Hoody □Jacket □Raincoat
□Others(Please specify)

Bottom:
□Base layer(bottom) □Sports pants □Shorts
□Others(Please specify)

4. Have you experienced any accident with cold water? Describe the experience.

Mobility

1. While you are rowing, which part do you think you need most mobility, please indicate below:

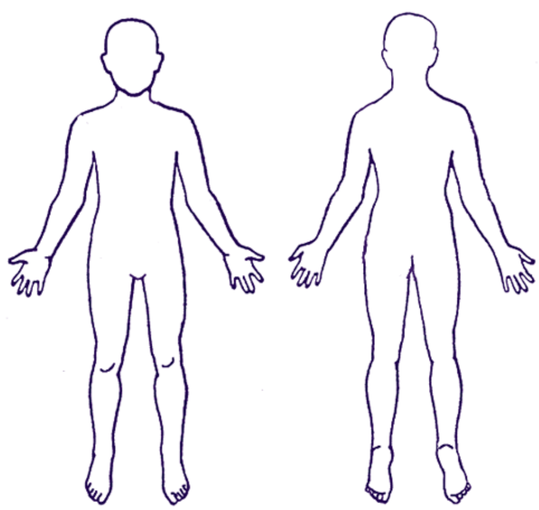


2. Which section did you feel impact of wearing PFD on your rowing motion?(If you have ever wore it) Please explain the nature of impact (e.g., compression, chaffing, mechanical restriction, etc.) in detail.

3. Compare compression garments (tight) and slack garments (loose) which do you think would have more influence on rowing motion? (Which gives you more mobility)

Thermal comfort

1. While you are rowing outside in **winter**, which area of your body do you feel thermally uncomfortable (e.g., feeling hot, sweaty, etc.)? Please indicate below:



2. How do you rate coldness/wind as one of the reasons that you might want to wear PFD in cold environment?

-3 -2 -1 0 1 2 3

-3: coldness/wind would not affect my decision at all
3: coldness/wind would totally affect my decision and it is the most critical reason

Phase2: Evaluation of influential characters of traditional PFDs

Perception of test PFD (rating+comments):

1. How do you feel about the size of the test PFD?

Too small	Slightly small	Neutral	Slightly large	Too large
-2	-1	0	1	2

2. How do you feel about the weight of the test PFD?

Very light	Slightly light	Neutral	Slightly heavy	Too heavy
-2	-1	0	1	2

3. How do you feel about the shape of the test PFD?

a. Front

Too narrow	Narrow	Neutral	Wide	Too wide
-2	-1	0	1	2

b. Profile

Too thin	Thin	Neutral	Thick	Too thick
-2	-1	0	1	2

4.How this PFD fits you?

Too tight	Slightly tight	Fit	Slightly oversize	Oversize
-2	-1	0	1	2

5.How do you rate earlier wearing PFD experience compare to our test PFD?

-3 -2 -1 0 1 2 3

-3 much worse than test PFD
-2 worse than test PFD
-1 slightly worse
0 almost the same
+1 slightly better
+2 better
+3 much better

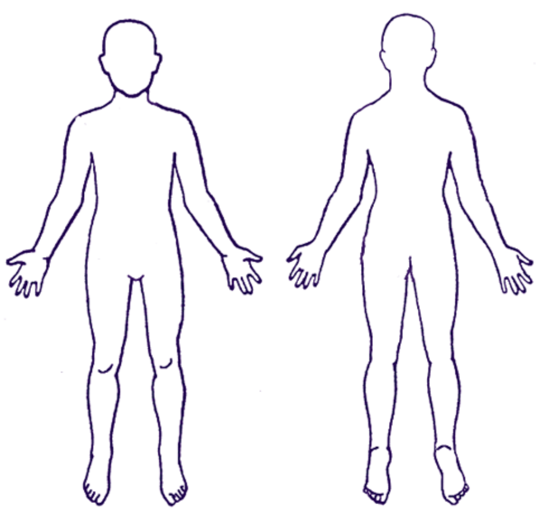
Mobility

1.How do you rate the mobility when rowing with PFD compare to without it?

-3 -2 -1 0 +1 +2 +3

-3 extremely restricted
-2 very restricted
-1 restricted
0 not restricted, just like NO PDF
+1 slightly better than without PDF
+2 better than without PDF
+3 much better than without PDF

2.Indicate (in the images below) which part have been affected and explain how the PFD affect that area?



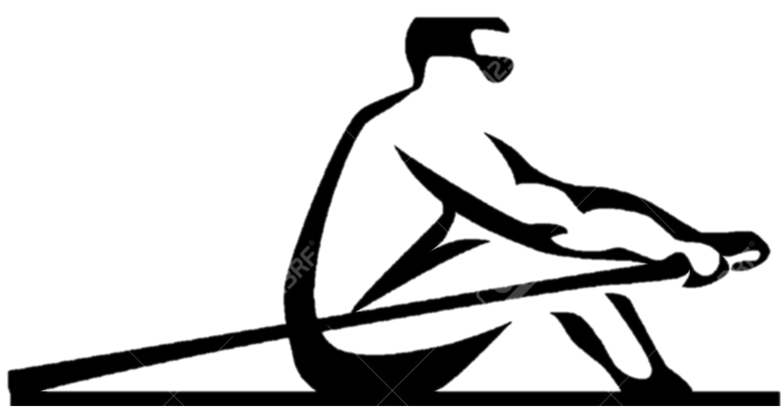
3. Which step in a whole stroke would have been most influenced by given PFD?

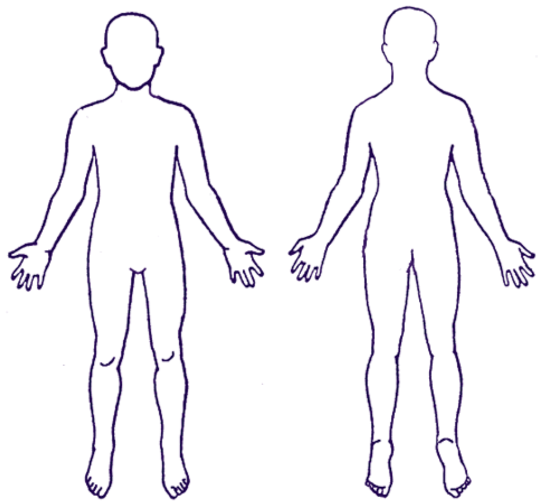
Please explain the nature of the impact in more detail.

Tactile comfort

1. How do you think about hands of the given PDF? If you experienced any tactile discomfort, please explain and also indicate the area of discomfort.
Did you experience prickling, chaffing, cling-ness, lack of stretch, or mechanical binding?
If you do, please explain in detail.

2.Indicate (in the images below) which part have experienced uncomfortable **pressure** and explain how? Circle the area and rate.
Please also rate the pressure level following this criterion:
-3 unbearable tight
-2 very tight
-1 tight
0 no uncomfortable pressure
+1 loose
+2 very loose
+3 too loose





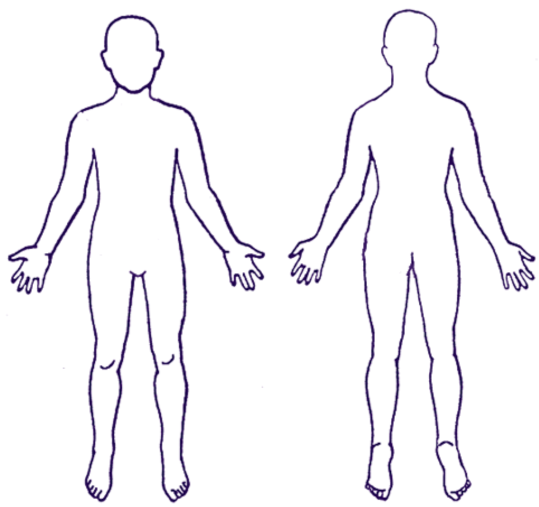
Thermal comfort

1.How do you rate the thermal comfort when rowing with PFD compare to without it?

-3 -2 -1 0 1 2 3

-3 Extremely uncomfortable
-2 Very uncomfortable
-1 Uncomfortable
0 **Neutral** status just like without PDF
+1 Comfortable
+2 Very comfortable
+3 Extremely comfortable

2.Indicate (in the images below) which parts you have experienced thermal uncomfortable and explain how?



-

Design Suggestions

1.Choose the PFDs that you are willing to wear in the options given by investigator and explain why.(see **PFD pictures** offered by investigator):

2. Are there other design features you wish to have on your new PFD?

3. Any other suggestions for improved design?

APPENDIX 2 POST-TEST QUESTIONNAIRE

1. Evaluation of Ease of Use

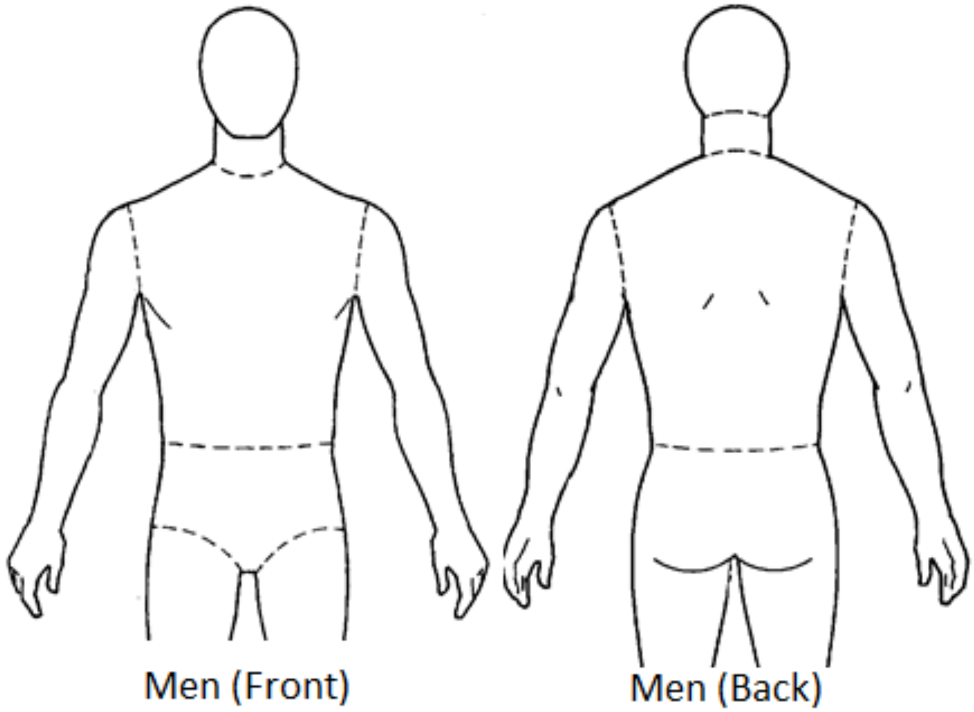
1.1 Donning and doffing

	Donning		Doffing	
	time	rating	Time	rating
Traditional PFD				
Prototype				

Please rate your level of convenience that you experienced while wearing as well as putting on and taking off the given PFD
(FILL IN THE CHART):

-3 Extremely Inconvenient
-2 Very Inconvenient
-1 Inconvenient
0 Neutral
1 Convenient
2 Very Convenient
3 Extremely Convenient

Comments/ extra description:



1.2 Ease of use:

Please rate your overall perception of *ease of use*.

Traditional PFD	
Prototype	

-3 Extremely difficult to use
-2 Very difficult to use
-1 Difficult to use
0 Neutral
1 Easy to use
2 Very easy to use
3 Extremely easy to use

2. Evaluation of size/fit/profile

2.1 How do you feel about the size of the test PFD?

Too small	Slightly small	Neutral	Slightly large	Too large
-2	-1	0	1	2

Traditional PFD	
Prototype	

2.2 How do you feel about the weight of the test PFD?

Very light	Slightly light	Neutral	Slightly heavy	Too heavy
-2	-1	0	1	2

Traditional PFD
Prototype

2.3 How do you feel about the shape of the test PFD?

a. Front

Too narrow	Narrow	Neutral	Wide	Too wide
-2	-1	0	1	2

b. Profile

Too thin	Thin	Neutral	Thick	Too thick
-2	-1	0	1	2

	Front	Profile
Traditional PFD		
Prototype		

2.4 How this PFD fits you?

Too tight	Slightly tight	Fit	Slightly oversize	Oversize
-2	-1	0	1	2

5.How do you rate Prototype PFD experience compare to traditional PFD?

-3 -2 -1 0 +1 +2 +3

-3 much worse than traditional PFD
-2 worse than traditional PFD
-1 slightly worse
0 almost the same
+1 slightly better
+2 better
+3 much better

3. Evaluation of mobility

3.1 How do you rate the mobility when rowing with PFD compare to without it?

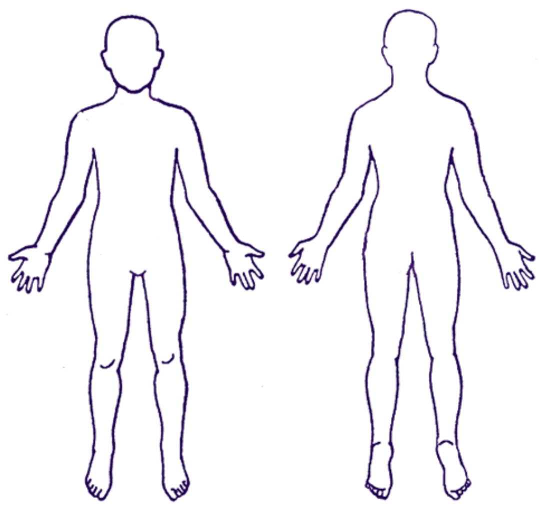
-3 -2 -1 0 +1 +2 +3

-3 extremely restricted
-2 very restricted
-1 restricted
0 not restricted, just like NO PDF
+1 slightly better than without PDF
+2 better than without PDF
+3 much better than without PDF

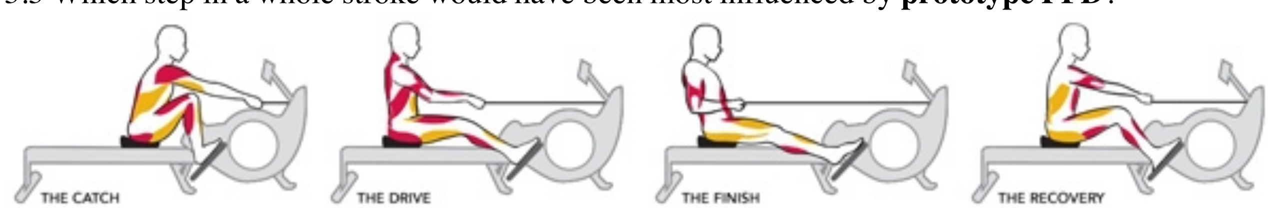
Traditional PFD	
Prototype	

For Prototype PFD only:

3.2 Indicate (in the images below) which part have been affected by the **prototype PFD** and explain how the PFD affect that area?



3.3 Which step in a whole stroke would have been most influenced by **prototype PFD**?



Please explain the nature of the impact in more detail.

4. Evaluation of Tactile comfort

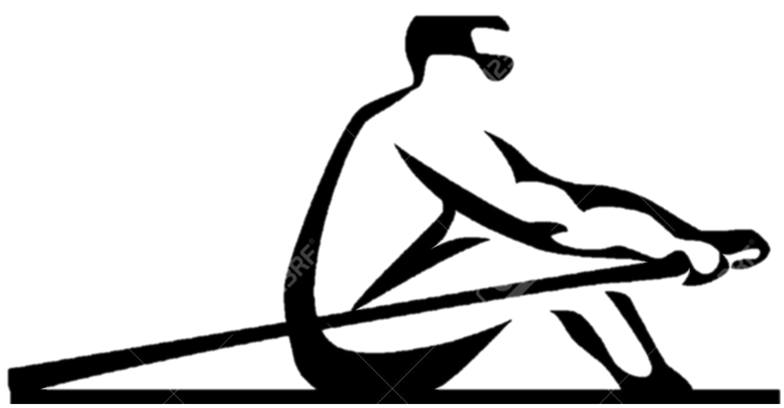
4.1 Please rate your overall perception of *tactile comfort*.

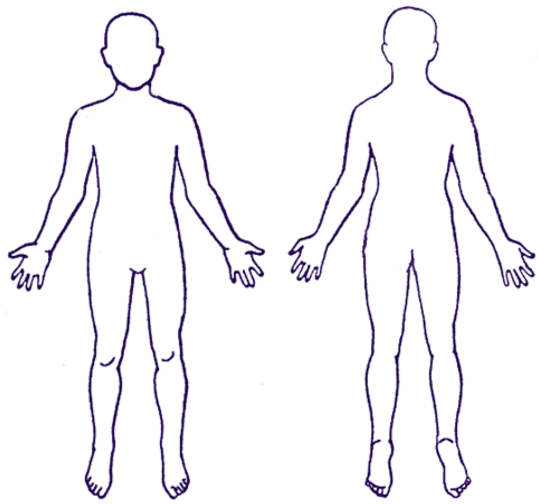
Traditional PFD	
Prototype	

-3 Extremely uncomfortable
-2 Very uncomfortable
-1 Difficult to use
0 Neutral
1 Comfortable
2 Very comfortable
3 Extremely comfortable

Did you experience prickling, chaffing, cling-ness, lack of stretch, or mechanical binding?
If you do, please explain in detail.

For Prototype PFD only:
4.2 Indicate (in the images below) which part have experienced uncomfortable **pressure** and explain how? Circle the area and rate.





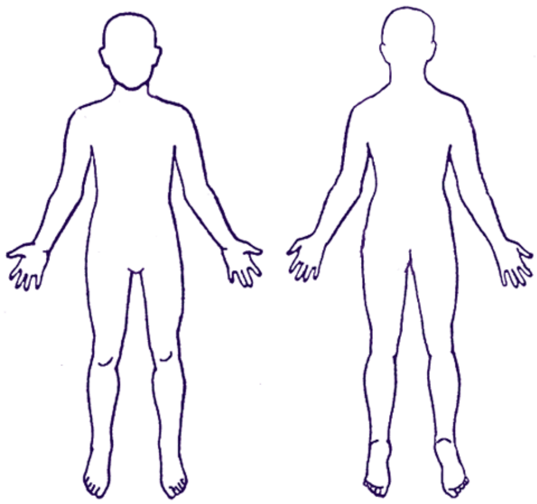
Thermal comfort

1.How do you rate the thermal comfort when rowing with prototype PFD compare to without it?

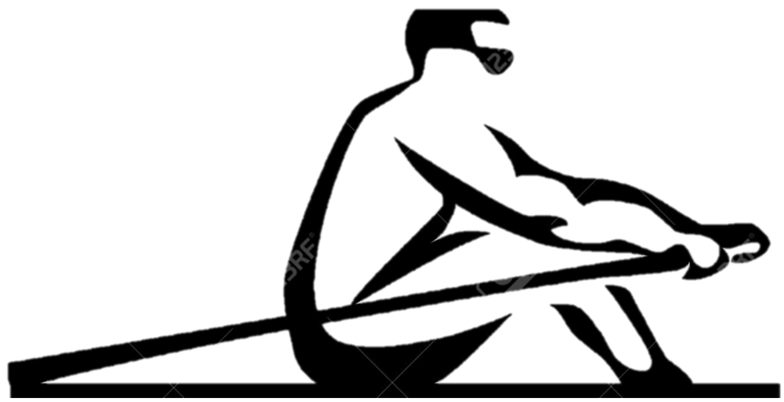
-3 -2 -1 0 +1 +2 +3

-3 Extremely uncomfortable
-2 Very uncomfortable
-1 Uncomfortable
0 **Neutral** status just like without PDF
+1 Comfortable
+2 Very comfortable
+3 Extremely comfortable

2.Indicate (in the images below) which parts you have experienced thermal uncomfortable and explain how?



-



Open – ended questions, how do you think about my prototype? Can you tell me what would be useful for your as a rower? What I should improve? What not work?

APPENDIX 3 IRB Ap

Cornell University
Office of
Research Integrity and Assurance

East Hill Office Building, Suite 320
395 Pine Tree Road
Ithaca, NY 14850
p. 607-254-5162
f. 607-255-0758
www.irb.cornell.edu

Institutional Review Board for Human Participants

TRIENNIAL PROTOCOL APPROVAL- NO FEDERAL FUNDS

To:	Manwen Li
From:	Carol Devine, IRB Chairperson
Protocol ID#:	1610006702
Protocol Title:	Study of Effect of Personal Flotation Device(PFD) on Performance of Rowers
Approval Date:	November 15, 2016
Expiration Date:	November 14, 2019

Carol M. Devine

Cornell University's Institutional Review Board for Human Participants (IRB) has reviewed and approved the inclusion of human participants in the research activities described in the protocol referenced above.

Special Conditions for Triennial Approval of this Protocol: This protocol was granted approval for three years until **November 14, 2019** as it does not involve federal funding and is therefore eligible for Triennial review under the IRB policy #21 (www.irb.cornell.edu/policy). As Principal Investigator for this project, you are responsible for informing the IRB and seeking re-review if at any point during the course of this project, Federal funds may be used to support any part of it. Failure to seek timely review and approval could result in an inability to use research data for the purposes of the Federal grant. Please refer to IRB policy #21 (www.irb.cornell.edu/policy) for more information.

The following personnel are approved to perform research activities on this protocol:

- Manwen Li
- Huiju Park

This approval by the IRB means that human participants can be included in this research. However, there may be additional university and local policies that apply before research activities can begin under this protocol. It is the investigator's responsibility to ensure these requirements are also met.

Please note the following important conditions of approval for this study:

1. All consent forms, records of study participation, and other consent materials **must** be held by the investigator for **five years** after the close of the study.