THESIS

# ANALYSIS OF BODY ARMOR FIT AND COMFORT USING 3D BODY SCANNING: A CASE STUDY WITH AN INDUSTRY PARTNER

Submitted by

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# ABSTRACT


ANALYSIS OF BODY ARMOR FIT AND COMFORT USING 3D BODY SCANNING: A CASE STUDY WITH AN INDUSTRY PARTNER

This study adopted a single case study approach to evaluate the fit and comfort of a company's body armor product, and improve the design of the product. To achieve this goal, I developed a mixed-methods strategy driven by the co-design paradigm and operated it in the three-stage product development process. A total of 13 individuals including five police officers and seven company employees participated in the study as collaborators for the product evaluation and development process. The police officers –actual users of the product – were recruited as external collaborators through the case company, and asked to participate in a series of data collection methods including the pre-survey, 3D body scanning, occupational task analysis, and exit interviews to provide holistic user feedback on the product. The company employees – developers of the product – were interviewed to share the insider's perspectives as internal collaborators. As results, key areas of interaction between the body and the vest were identified during Stage 1 (Problem Definition and Research), which subsequently informed the creative design and prototyping process in Stage 2 (Creative Exploration and Evaluation). During Stage 3 (Implementation), final recommendations and plans for implementation were developed with the case company. The outcome of this research is expected to benefit the case company who manufactures the body armor product, as well as police officers who wear it in the line of occupational duty, as the resulting product will offer better fit for their body and be more comfortable to wear.

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# CHAPTER 1: INTRODUCTION

In the current political and cultural climate, safety and physical protection are of concern for many, including law enforcement officers and those who outfit them with necessary safety garments. Since 2009, firearm assault has been a leading cause of death in law enforcement officers, killing more officers each year than any other job-related illness or non-vehicle related injury (National Law Enforcement Officers Memorial Fund [NLEOMF], 2018; U.S. Department of Justice, Federal Bureau of Investigation [US DOJ FBI], 2018).

Body armor is the tactical vest commonly worn by police officers that provides protection from bullets and ballistic threats (Office of Law Enforcement Standards & United States of America [OLES USA], 2008). The use of body armor has been shown to substantially improve the likelihood of survival following ballistic impact within the coverage area by as much as four times (LaTourette, 2010; Liu & Taylor, 2017b). In fact, it has been reported that since 1972, more than 3,000 police officers have been saved because they were wearing body armor when they encountered a ballistic threat ("IACP/DuPont™ Kevlar® Survivors' Club®", 2017; James, 2016).

Despite of the protective benefit of wearing the body armor, officers may not use body armor, or may mis-use it even at the risk of their own life and safety (Dunne & Smyth, 2007). Police officers have long had access body armor, but may have the choice if or when to wear it (Grant, et al., 2012). Reports indicate that between 2007 and 2017, only 61% of the officers killed were wearing body armor at the time of the assault. Discomfort or improper fit contribute to officers choosing not to wear body armor (Liu and Taylor, 2017a; Barker, 2007; Basich, 2008; Burton, 2018). Previous research shows that wearing body armor is often an uncomfortable experience for the wearer (e.g. Barker, 2007; Barker & Black, 2009; Fowler, 2003). Consequently, wearing uncomfortable or ill-fitting body armor can negatively affect mobility, speed, and accuracy of physical tasks performed by police officers in the line of duty (Barker, 2007; Barker & Black, 2009; Dempsey, Handcock, & Rehrer, 2013; Fowler, 2003; Lee, Hong, Kim, & Lee, 2013). Furthermore, wearing body armor can cause lower back pain and injury due to excessive weight on the torso of the wearer (Burton, Tillotson, Symonds, Burke, & Mathewson, 1996).

To gain practical insight into the discomfort that police officers experience from wearing the body armor, this study adopted a single case study approach. The case company chosen for this study had evidence that customers were experiencing some discomfort and fit issues with the original model of the company's body armor. The case company had need of investigation into the causes of the discomfort and reported fit issues, as well as recommendations and validation of technical design changes that will solve the problems. The case company's needs, along with contemporary issues of police officer's occupational injury and wearer resistance of body armor, encouraged this research effort. Furthermore, previous researchers had called for the imperative nature of this research topic for occupational safety of police officers and the communities they serve (Barker & Black, 2009; Flower, 2003; Park, Nolli, Branson, Peksoz, Petrova, & Goad, 2011).

**Statement of Purpose**

The purpose of this study was to identify and improve the fit and comfort issues surrounding the case company's current body armor design. Through suggestions for improving the technical design and fitting practice of the case company, I hoped the research outcomes would reduce the number of products returned to the case company due to lack of fit, as well as provide a more wearable product for law enforcement officers. The lessons learned from this study were anticipated to provide insightful guidance for other manufacturers and stakeholders in solving fit and design problems associated with body armor, with a hope to lower human factors barriers in adopting the protective shield among police officers. This research will employ a three-stage process model used to organize the overarching philosophy of co-design which drives this research. The theory driven goals of this study include an assessment of the value of co-design in facilitating a product development driven industry-university collaboration. To achieve these research goals I developed specific research questions presented in the next section.

**Research Questions**

The following questions are developed to attain the purpose of this study:

RQ1: What areas of the body interact with the body armor vest to influence the fit and comfort of the case company's body armor?

RQ2: How can the functional design elements of the body armor be manipulated to improve fit and comfort of the case company's body armor at the areas identified in RQ1?

The aforementioned research questions were investigated within the conceptual framework called co-design (Sanders & Stappers, 2008). Co-design is a democratic design paradigm that is based on the premise that 'users' are the experts of their own domain and should be actively involved in the design process. Specifically, I explored benefits of using the co-design philosophy in the university-industry collaboration project, which involved various stakeholders inside and outside the case company. Therefore, my last research was as follows:

RQ3: Does the co-design philosophy add value in product development process for a university-industry collaboration?

## Scope

A single case company was chosen for the current investigation of body armor. Because the company has evidence of fit problems occurring in their original body armor model, this study focused on the fit and comfort of that model only. The original body armor model is designed to be versatile and can be worn under two conditions: The carrier vest can be outfitted with or without hard ballistic plates (in front and in the back of the vest). The particular focus of this study was anthropometric fit and associated functional design of the body armor and how the proposed changes affect the comfort of the participants under both the plated and non-plated conditions. Study participants included 1) seven company employees (i.e., those who are already employed within the case company) and 2) five product users of the case company (i.e., police officers from local stations). Police officers were chosen as specific user participants for this study because they are the primary customers of the case company and wearers of the body armor. Additional participant recruitment criteria are detailed in Chapter Three.

## Definitions

**Body Armor:** "An item of personal protective equipment that provides protection against specific ballistic threats within its coverage areas… the term body armor refers to that which provides coverage primarily for the torso" (OLE USA, NIJ Standard- 01010.06, 2008, p.7).

**Armor Carrier or Carrier Vest:** A component of body armor, the primary purpose of which is to carry the ballistic panel and/or plates. The carrier "provides a means of supporting and securing the armor garment to the user" (p. 6). The carrier does not always have ballistic resistance without the panels and/or plates inserted (OLE USA, NIJ Standard- 01010.06, 2008). The word 'carrier,' if not preceded by the word 'ballistic,' refers to an armor carrier in this study.

**Armor Panel or Panels:** The portion of a body armor product that consists of an external ballistic cover and its internal ballistic panel. The armor panel is typically inserted into the carrier. The word ‘panel,’ if not preceded by the word ‘armor,’ refers to an armor panel in this study. (OLE USA, NIJ Standard- 01010.06, 2008).

**Ease (aka Functional Ease):** The mathematical difference between the size of the garment and the body measurement at a specified point. Functional ease is included in a garment to allow for minimum necessary mobility. The appropriate amount of functional ease is subjective, and varies from product to product. Too much or too little ease can negatively affect the fit and comfort of a garment (Keiser & Garner, 2008). The equation for functional ease is expressed as: *Garment measurement at point A – Body measurement at point A = Functional ease at point A*

**Fit:** The way the garment conforms to the shape and size of the individual wearing it (Keiser & Garner, 2008).

**Comfort:** “a mental state of ease or well-being, a state of balance or equilibrium that exists between … [an individual] and their environment” (Maher & Sontag, 1995;1995; Fowler, 2003). Overall perceptions of comfort are a composite of physical, psychological and physiological comfort perceptions (Li, 2010).

**Prototype:** The first product or garment made from a pattern. It provides the developer with information about the cost, fit, and comfort of the design. Evaluation of the prototype can be used to provide the developers information about possible problems with the design before full production of the product is undertaken (Keiser & Garner, 2008).

**Type IIIA Body Armor:** This level of body armor is resistant to .357 SIG; .44 Magnum type bullets (OLE USA, NIJ Standard- 01010.06, 2008).

**Type III Body Armor:** This level of body armor is resistant to 7.62 mm full metal jacket, steel jacketed rifle bullets.

# CHAPTER 2: LITERATURE REVIEW

The review of literature for this research begins with a synthesis of the literature on anthropometrics and 3D body scanning in the apparel and product development field. A review of the relevant processes and frameworks used in the field to drive successful product development projects is presented with the focus on co-design methodology and Three-Stage Design Process developed by LaBat and Sokolowski (1999). What follows is a review of previous studies specific to body armor including key background information on body armor; body armor and psychological wellbeing; mobility and range of motion; body armor and physiological well-being, body armor fit and comfort; and conclusions about the existing work on body armor.

## Anthropometrics and 3D Body Scanning

Anthropometry, the scientific study of the measurements and proportions of the human body, is vital for creating garments and wearable products with accurate fit for the wearer (Watkins & Dunne, 2015). In the apparel and product development field, anthropometry is used to generate sizing systems for the ready to wear industry. Anthropometric data are often utilized to create custom fitted garments, as well as to identify and improve the fit of products for the mass market (Watkins & Dunne, 2015).

Over the last two decades, advances in technology have developed for anthropometric data to be collected using three-dimensional (3D) full body scanning (Daanen & Ter Haar, 2013). A thorough review of the history and technical backgrounds of 3D body scanning is beyond the scope of this literature review but a comprehensive history may be found in a study by Simmons and Istook (2003). The innovations in 3D body scanning have increased the speed and accuracy of anthropometric measurement when compared to the previous practice of measuring the human body manually with a soft measuring tape (Daanen & Ter Haar, 2013; Simmons & Istook, 2003). This manual practice of measuring body dimensions is taught widely to home sewers, and professional fashion designers alike. It is one of the first lessons in most sewing and pattern drafting text books (Armstrong, 2006; Knowles, 2005; McCall's, 1968; Singer, 1990) because accurate body measurements are essential to creating a garment that fits the body (Watkins & Dunne, 2015).

Previous studies have attempted to compare the various body scanners available on the market (Daanen & Ter Harr, 2013; Simmons and Istook, 2003). The study by Simmons and Istook (2003) compared the landmarks used for body measurement in three different body scanner models with the standard landmarks from a seminal pattern drafting method. Simmons and Istook (2003) found that each body scanner model was taking body measurements from different body landmarks. Thus, authors criticized the body scanning manufacturers for the lack of a common standard in measurement output, and lack of transparency when they attempted to research this matter. The study (Simmons & Istook, 2003) determined that the $[TC]^2$® scanner's body landmarks were the best aligned with what would be expected in the apparel industry. Daanen and Ter Haar (2013) were comparing the basic technology systems that can be used to in 3D scanning systems. According to the researchers (Daanen & Ter Haar, 2013), the 3D scanning systems include laser line systems, structured light systems, infrared systems, multiple camera systems and millimeter wave systems. The study by Daanen and Ter Haar (2013) did not face the same problems with transparency as Simmons and Istook (2003). This could mean that body scanning manufacturers have begun providing more information to the public about their system in the years since Simmons and Istook's (2003) study.

Reliability of the anthropometric data has been widely discussed in the literature relevant to 3D body scanning technology. When the technology emerged, experts created algorithms to digitally identify landmarks on the body and capture body measurements (Lu & Wang, 2008; Wang, Wu, Lin, Yang, & Lu, 2007). Three-dimensional body scanning has been shown more reliable body measurements than those taken by the manual method (Lu & Wang, 2008; Wang et al., 2007). [TC]$^2$®, a leading 3D body scanning manufacturer, reports that their product captures circumferential body measurements within approximately 3mm of the true measurement ([TC]$^2$®, 2012).

Previous researchers have experienced success when using 3D body scanning to obtain anthropometric data for identifying problems with fit and comfort of apparel and wearable products (Ashdown, Loker, Schoenfelder, & Lyman-Clark, 2004; Park & Langseth-Schmidt, 2016). One of the first studies using 3D body scanning for fit analysis (Ashdown et al., 2004) scanned 250 female participants and used the data to evaluate the current sizing system of women's pants and conduct virtual fit sessions using a 3D modeling software. The authors reported many advantages including the ease with which they could see fit issues, and compare many virtual models side by side to compare fit between body types. Further, Park and Langseth-Schmidt (2016) used 3D body scanning to compare the fit of uniform pants worn by male and female firefighters. Their efforts revealed meaningful insights into potential occupational injury risks associated with the fit of the firefighter's uniform pants, particularly for female firefighters who wear a protective uniform designed for the male physique. In conclusion, the use of 3D body scanning has been shown to be a reliable and helpful tool in the evaluation of garment fit (Ashdown et al., 2004; Park & Lanseth-Schmidt, 2016).

## Conceptual Framework and Process Models

### Co-design

Co-design (sometimes used interchangeably with collaborative design or participatory design) can be characterized by involving various stakeholders in the design process (Sanders & Stappers, 2008). This includes bringing traditional designers, researchers, businesses, and users of the product to the table to explore ideas and possibilities (Fuad-Luke, 2009). There is no standard model or process for co-design. Rather the co-design methodology has been envisioned differently by various scholars and is generally viewed as a flexible paradigm (Visser, Stappers, van der Lugt, & Stappers, 2005).

Through co-design, stakeholders are given new roles which are meant to nurture collaboration. The researcher acts as a facilitator among the parties, and guides them to participate in the design process (Sanders & Stappers, 2008). Other collaborators (i.e. users and businesses) should be considered experts of their own experiences regarding product use and their needs related to the product (Sanders & Stappers, 2008). The role of the user may be as a resource, co-creator, product tester, or a combination of these (Morris, 2011; Nambisan, 2002). The designers are responsible for bringing the ideas of the collaborators to life (Sanders & Stappers, 2008; Visser et al., 2005). It has been suggested that designers should also strive to take on different roles (i.e. facilitator, user, etc) throughout the process to better understand the various stakeholders (Lee, 2008).

Co-design had been established a strategy for generating successful prototypes both when developing physical tools and virtual systems (Björgvinsson, 2008; Visser et al., 2004). It has been suggested that collaboration, especially for prototype development is most successful when the collaborators establish a long-term relationship (Björgvinsson, 2008). Although there is no single model, the best practices for this type of long-term collaboration have been explored in models that integrate previous classic knowledge of product development processes and co-design strategies. Examples of this include the Collaborative Apparel Product Development (CAPD) Model by Morris (2011) which can be seen in Figure 1.1.

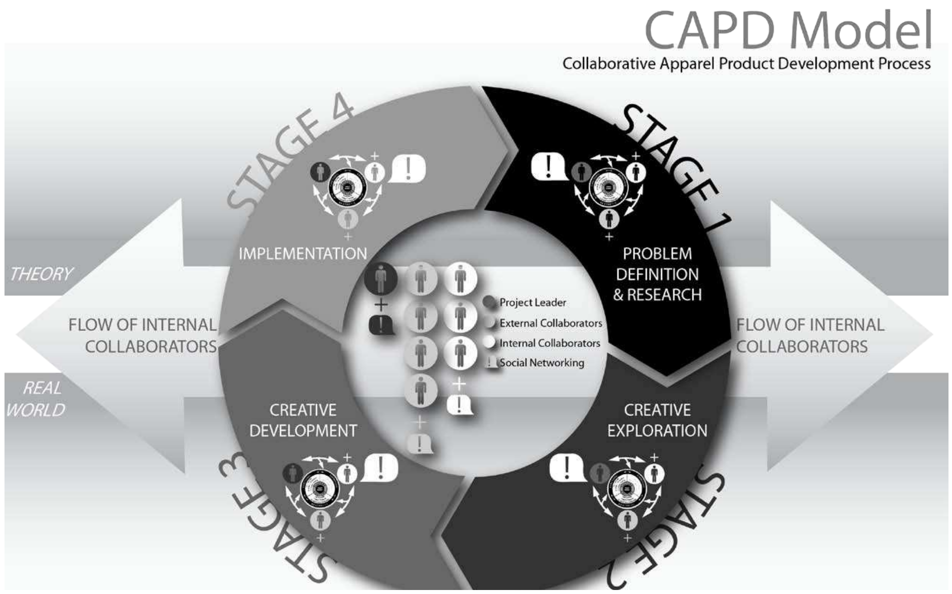


***Figure 2.1:*** *CAPD Model by Morris (2011)*

The CAPD Model (Morris, 2011) is an integration of the philosophies of co-design with a process model for product development (adapted from LaBat & Sokolowski, 1999). The role of internal and external collaborators in each stage revolves around the Functional, Expressive, Aesthetic Model by LaBat and Kallal (1994).

**The Three-Stage Design Process**

After a broad review of potential process models, a three-stage product development process will be adopted to organize and drive the current research inquiry. The Three-Stage

Design Process by LaBat and Sokolowski (1999) was developed to guide the industry-university collaboration. LaBat and Sokolowski's process utilized ideas from architecture, environmental design, engineering, industrial product design and clothing design processes. The result is an integrated process that outlines the following three stages to successful product development: 1) Problem Definition and Research, 2) Creative Exploration, 3) Implementation (LaBat & Sokolowski, 1999).

During the first stage, *Problem Definition and Research,* it is suggested that the design problem be assessed from the client's perspective to define user and market needs. The identified needs should also be assessed to create a working problem definition (LaBat and Sokolowski, 1999). The second stage *Creative Exploration* is described as the least defined stage in the model by LaBat and Sokolowski (1999). It is recommended that the researcher begin by exploring all the possibilities for solving the design problem. Only after all possibilities have been explored, the design ideas are refined. The refined ideas are then implemented into a prototype. The third stage, *Implementation*, involves the case company working with the researcher to implement the recommendations of the researcher into their product development process. LaBat and Sokolowski (1999) specifies that implementation may be done in multiple phases if time or cost prevent the cast company from making changes all at once. Details of The Three-Stage Design Process (LaBat &Sokolowski, 1999) can be found in Table 2.1. The model was first conceptualized to guide and structure collaboration between university students and industry partners. Previous researchers have found success in using the model for this purpose (Bye & Hakala, 2005) including a study on body armor design (Tung, 2008).

***Table 2.1:*** *Three-Stage Design*

| Stage 1: Problem Definition and Research | Stage 2: Creative Exploration | Stage 3: Implementation |
|---|---|---|
| A._Initial Problem Definition<br>• Client definition | A._Preliminary Ideas<br>• Expansive, all realm of possibilities. | A._Production Refinement<br>• Cost to produce<br>• Time to produce<br>• Methods of production<br>• Sales potential |
| B._Research<br>• User Needs: function, aesthetic, economic.<br>• Market: assess current products, competitive analysis, economic conditions. | B._Design Refinement<br>• User constraints: function, aesthetic, economic.<br>• Product constraints: cost to produce, methods of production, sales potential. | B.Phase 1: Immediate Production<br>• Changes in product or production that can be accomplished immediately. |
| C._Working Problem Definition<br>• Defined by industry client and university designer.<br>• Design criteria established | C._Prototype Development<br>• Mesing design criteria and constraints to develop workable ideas. | C._Phase 2: Improvement/Refinement<br>• Further development that may be delayed |
| | D._Evaluation of Prototype<br>• Preliminary: by university designer.<br>• Final: by university designer and industry client | |

Note: By LaBat and Sokolowski (1999)

**Integrative Process Model Used in This Study**

Co-design was the overarching philosophy guiding the study, with a three-stage process model (LaBat & Sokolowski, 1999) used to organize the implementation of co-design into the product development investigation. The diagram in Figure 2.2 displays the proposed integration of these two strategies. Strategies and methods for co-design are embedded in each stage of the process. The first stage, *Problem Definition and Research*, incorporates input from the internal and external collaborators to determine the needs of the case company and product users respectively. These needs are evaluated to define the research and problems to be investigated in the *Creative Exploration and Evaluation* stage (stage 2), where all possible solutions to the design problems are explored based on the collaborators' inputs. In this stage, prototypes are developed and evaluated with internal and external collaborators. Finally, in stage 3, *Implementation*, the outcomes from stages 1 and 2 are discussed and internal collaborators develop plans for short term and long term implementation of the final recommendations.

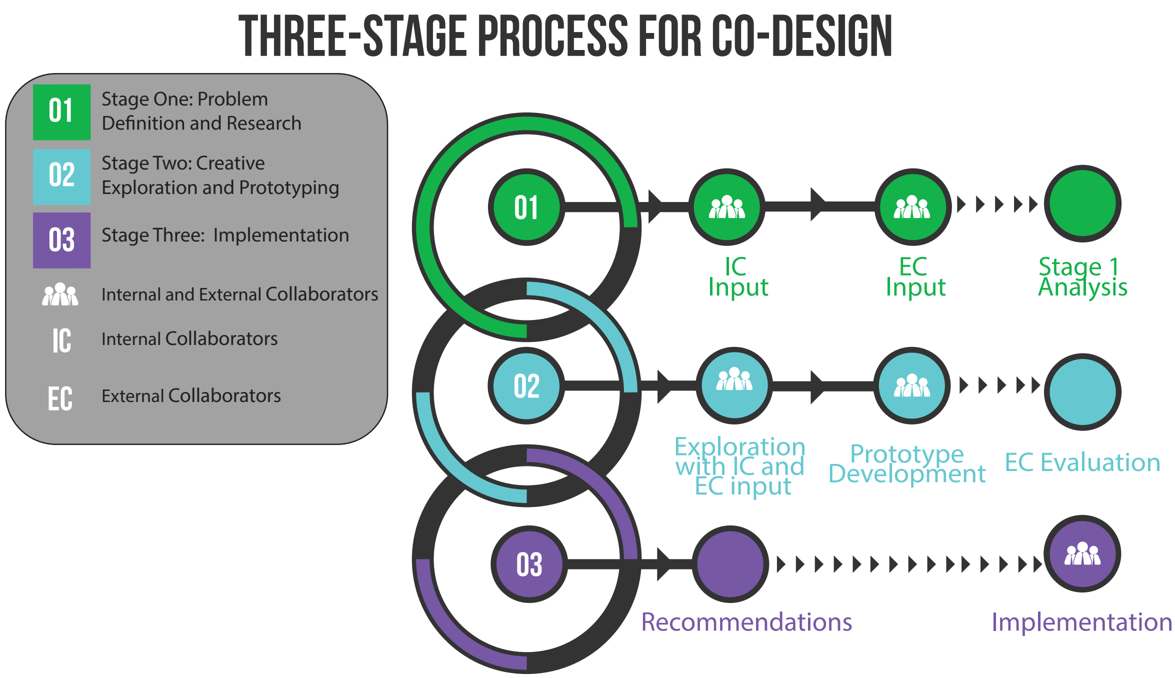


***Figure 2.2:*** *Integrative Process Model*

**Key Background on Body Armor**

The key background information of the target project is provided to clarify how body armor is defined for the purpose of this study. This section will also discuss levels of protection in body armor and other terms pertaining to body armor and its components.

## Definition of Body Armor

In the 2008 publication titled "Ballistic Resistance of Body Armor", the United States Government defines body armor as "an item of personal protective equipment that provides protection against specific ballistic threats within its coverage area. In this standard, the term body armor refers to that which provides coverage primarily for the torso" (OLES USA, 2008, p. 7). Armor designed to protect areas of the body other than the torso will not be explored in this study. Although there are a variety of terms and definitions for this protective system, within this literature review the terminology and definition of body armor will be derived from the protocol set forth by the OLES USA (2008). In further support of using the term 'body armor,' it has been assessed to be the most widely used term across the literature (Caldwell, Engelen, van der Henst, Patterson, & Taylor, 2011; Hasselquist, Bensel, Corner, Gregorczyk, & Schiffman, 2008; Lee et al., 2013; Park et al., 2011; Ricciardi, Deuster, & Talbot, 2008).

## Levels of Protection of Body Armor

The research resulting from this literature review will be conducted in the United States. For this reason, the method of classifying body armor is consistent with that of the OLES USA (2008, p. 7). Five levels of body armor protection are provided by the OLES USA (2008, p. 7) and are categorized from least to most protective using the terms Level IIA, Level II, Level IIIA, Level III, and Level IV. A body armor garment is assigned to one of these levels based on the type of bullet it can withstand and prevent penetration to the wearer (OLES USA, 2008). More information about the Levels of body armor may be found in the following text and in Table 2.2.

**Soft body armor.** Level IIA, Level II and Level IIIA body armor are typically made as soft armor (United States Department of Justice [US DOJ], 2014, p. 6), meaning it is constructed from multiple layers of textile materials. The textile materials can include Kevlar®, Goldflex®, ArmorFelt®, Spectra®, or Dyneema® (Barker & Black, 2009; Barker, Black, & Cloud, 2010; OLES USA, 2008). Level IIA body armor is the least protective of the categories. Body armor garments with this classification are resistant to handgun bullets such as 9 mm and .40 caliber Smith and Wesson bullets traveling at lower velocities (OLES USA, 2008). Level II body armor is resistant to handgun bullets of the 9 mm and .357 Magnum caliber (OLES USA, 2008). Level IIIA body armor is resistant to .357 SIG and .44 Magnum caliber bullets (OLES USA, 2008). Soft body armor is known to be more flexible than hard body armor. This often results in a lower level of protection (US DOJ, 2014).

**Hard body armor.** Level III and Level IV are typically hard armor (US DOJ, 2014). This means they are constructed from ceramics, metals, laminates, or composites (US DOJ, 2014; see also Caldwell et al., 2011; Lee et al., 2013; Majchrzycka, Brochocka, Łuczak, & Łężak, 2013; Park et al., 2011). Level III body armor is resistant to rifle bullets (OLESOLES USA, 2008). Level IV is the most protective category of body armor and is resistant to armor piercing rifle bullets (OLES USAUSA, 2008).

*Table 2.2:* *Types of body armor*

| Armor Type | Armor Level | Description of an unconditioned model's resistance to ballistics. |
|---|---|---|
| Soft Body Armor | Level IIA | 9mm full metal jacket round nosed (FMJ RN) bullets with specified mass of 8.0g and a velocity of 373 m/s ±9.1 m/s<br>.40 S&W FMJ bullets with a specified mass of 11.7 g and a velocity of 325 m/s |
| | Level II | 9mm FMJ bullets with a specified mass of 8.0 g and a velocity of 398m/s.<br>.357 Magnum Jacketed Soft Point JSP bullets with a specified mass of 10.2 g and a velocity of 408 m/s. |
| | Level IIIA | .357 SIG FMJ Flat Nose (FN) bullets with a specified mass of 8.1 g and a velocity of 448 m/s.<br>.44 Magnum Semi Jacketed Hollow Point (SJHP) bullets with a specified mass of 15.6 g and a velocity of 436 m/s. |
| Hard Body Armor | Level III | 7.62 mm FMJ, steel jacketed bullets with a specified mass of 9.6 g and a velocity of 847 m/s. |
| | Level IV | .30 caliber armor piercing (AP) bullets with a specified mass of 10. G and a velocity of 878 m/s. |

Note: Adapted from OLES USA (2008) All velocity speeds in meters per second have a tolerance of ± 9.1 m/s. (OLES USA, 2008).

**Other Terms of Body Armor**

There are multiple components that make up the torso protection system called 'body armor' as described by The US DOJ (2014). The term 'carrier' will be used to refer to the vest garment that is worn in order to carry the protective inserts on the body. The carrier is designed with pockets that plates can be secured in, often allowing the user to remove or change the plates if necessary (US DOJ, 2014).

Plates or plate inserts (PI) refer to the mechanism that actually prevent bullets from penetrating the body. Plates or plate inserts are defined as "hard armor plates or semi-rigid plates that are intended to be inserted into pockets of flexible vests and jackets to provide increased protection, particularly to provide protection against rifle threats." (OLESOLES USA, 2008, p.

7). The term panel is used to describe the layers of textile materials that create soft armor. Panels also may be inserted into the pockets of carrier vests (Barker et al., 2010), although some manufacturers also sew the panels permanently into the body armor carrier. Panels are designed to provide protection to the wearer from ballistic threats (US DOJ, 2014).

## The Effects of Wearing Body Armor

The effect of wearing body armor (as compared to wearing no body armor) has been well documented in the exiting body of literature. Findings suggest that wearing body armor may have negative effects on the wearer's physical (Demsey et al., 2012; Hasselquist et al., 2008; Park et al., 2011; Ricciardi et al., 2008), physiological (Caldwell et al., 2011; Cheuvront, Goodman, Kenefick, Montain, & Sawka, 2008; Hasselquist, et al., 2008; Montain, Sawka, Cadarette, Quigley, & McKay, 1994; Ricciardi et al., 2008), and psychological wellbeing (Caldwell et al., 2011; Majchrzycka et al., 2013). A brief overview of the key literature concerning the effects of body armor on the wearer is included here. Additional information and in-depth reviews of this topic may be found in several recently published meta-analyses (e.g. Joseph, Wiley, Orr, Schram, & Dawes, 2018; Larsen, Netto. & Aisbett, 2011; Schram, Hinton, Orr, Pope, & Norris, 2018; Tomes, Orr, & Pope, 2017).

### Physical State

Both male and female military personnel saw a significant reduction in the number of stairs they could climb per minute when their test-times were compared for the experimental phase of wearing body armor and the control phase of wearing a t-shirt and exercise short (Ricciardi et al., 2008). The test garment in Montain et al.'s 1994 study was not body armor, but the findings are worth noting here because this study seems to have set methodological precedence for many subsequent inquiries concerning physical performance and personal protective equipment. The author describes a protective ensemble that when donned significantly reduced exercise time in healthy soldiers. Exercise in this study was defined as the ability of the soldier to continue walking on a treadmill (Montain et al., 1994).

Male military personnel wearing body armor were found to experience reduced performance in number of pull ups they could complete before fatigue. (Dempsey et al., 2013; Ricciardi et al., 2008). Female military personnel were less able to hold their body weight with arms flexed and chin above a pull up bar while wearing body armor when compared to completing the same task without body armor (Ricciardi et al., 2008). Mobility task performance was significantly affected by the added load of wearing stab resistant body armor when compared to wearing no such body armor (Dempsey et al., 2013). The tasks affected include a 5-minute run, balance task, an acceleration task, and a grappling task. (Dempsey et al., 2013).

**Mobility and Range of Motion.**

Some upper and lower body motions were reduced in range for men who are wearing body armor (as opposed to no body armor) (Dempsey et al., 2013; Hasselquist et al., 2008; Park et al., 2011). The range of motion in the pelvic area showed the most alarming reduction for lower body motions (Park et al., 2011). Pelvic intra-rotation and extra-rotation as well as pelvic anterior and posterior tilt were significantly affected when participants wore body armor as opposed to when they wore only a tank top and athletic shorts. (Park et al., 2011). This means participant’s pelvic area was limited in the ability to move forward (anterior tilt) and backward (posterior tilt) as well as limited in the ability to rotate inward (intra-rotation) and outward (extrarotation; Park et al., 2011). Upper body mobility may be reduced by 13-42% when wearing body armor (as opposed to no body armor) when mobility is measured by the participant's ability to complete tasks such as running, chin-ups, balance and other mobility challenges that may be performed by an on-duty police officer (Dempsey et al., 2013).

Gait analysis, when used as measure of range of motion, showed significant changes in walking patterns for participants when wearing body armor, as opposed to when wearing no body armor (Hasselquist et al., 2008; Larsen, 2018; Park et al., 2011). The findings show significant reduction in range of motion for gait factors of swing phase, swing time, and double support time. This means participants exhibited less range of motion when moving their feet forward (swing phase), their feet spent less time off the ground when moving forward (swing time) and they spent more time with both feet on the ground at the same time (double support time; Hasselquist et al., 2008; Park et al., 2011).

**Physiological State**

**Heart rate.** There is overwhelming evidence to support the notion that wearing body armor has negative effects on the physiological responses of the wearer. By far, the most researched and well agreed upon topic is that wearers experience a significant increase in heartrate when wearing body armor, as opposed to wearing no body armor (Caldwell et al., 2011; Cheuvront et al., 2008; Montain et al., 1994; Ricciardi et al., 2008). The increase in heartrate while wearing body armor has remained evident in exercise tests completed in hot and humid climates (Caldwell et al., 2011; Montain et al., 1994), after becoming acclimated to hot and dry climates (Cheuvront et al., 2008; Montain et al., 1994) and at room temperature (Ricciardi et al., 2008).

**Oxygen consumption.** Other physiological effects of wearing body armor include increased oxygen consumption (Hasselquist et al., 2008; Ricciardi et al., 2008). When comparing the oxygen consumption of participants who completed exercise tests wearing body armor, as compared to when not wearing body armor, Hasselquist et al. (2008) found no statistically significant change in oxygen consumption. Testing similar conditions, Ricciardi et al. (2008) found oxygen consumption to increase 12-17%. The discrepancy in these findings may be caused by the fact that the body armor tested by Ricciardi et al. (2008) weighed 1.3 kg more than the body armor tested by Hasselquist et al. (2008).

**Sweat loss.** A significant increase in sweat loss was found in male participants wearing body armor when compared to their sweat loss while wearing no body armor (Caldwell et al., 2011; Cheuvront et al., 2008). It must be noted that Cheuvront et al. (2008) questioned the consequence of their own findings by stating the magnitude of change was statistically significant but of "questionable practical importance" (p. 581).

**Blood lactate levels.** Levels of blood lactate have been shown to increase in military personnel between tests taken after completing exercises while wearing body armor as compared to tests taken after completing exercises without body armor (Ricciardi et al., 2008). According to Ricciardi et al. (2008), the high levels of blood lactate suggest that wearers were experiencing, or were about to experience muscle fatigue.

**Psychological State**

There is some conflicting evidence regarding the possible effect of wearing body armor on the psychological and cognitive wellbeing of the wearer (Caldwell et al., 2011; Majchrzycka et al., 2013; Roberts & Cole, 2013). Caldwell et al. (2011) reported that there was no meaningful change in cognitive function but Majchrzycka et al. (2013) and Roberts & Cole (2013) both reported that participants showed signs of mental fatigue after performing physical tasks in the body armor. This suggests that wearing body armor may have a negative effect on the wearer's psychological state (Majchrzycka et al., 2013, Roberts & Cole, 2013).

## The Fit and Comfort of Body Armor

A limited number of studies were found that explored the fit of body armor. The studies that have researched this topic reveal that the neck and waist areas of the body armor vest all present problems with fit (Barker, 2003; Fowler, 2003; Tung, 2008). Tung's study (2008) evaluated the fit of female military soldiers only, wearing Level IV body armor, but the findings of other studies (Barker 2003; Fowler, 2003) show that women are experiencing some of the same fit problems as male police officers.

Participants in multiple studies reported that the neck area of the body armor was too tight (Barker 2003; Fowler, 2003; Tung, 2008). Women in Tung's study (2008) reported that the tight neckline often created a choking feeling. Tung (2008) suggested reshaping the neckline to accommodate for this. Even though the new neckline shape would result in less protective coverage, this was considered preferable to the discomfort of the standard neckline (Tung, 2008). Barker (2007) conducted a survey of 91 male police officers wearing Level II body armor and found that 60.7% of the participating officers rated their vest was tight around the neckline when standing.

Participants in multiple studies reported that the waist areas of body armor were ill-fitting. Although body armor fit was outside of the scope of Fowler's study (2003), the author received comments from participants about their dissatisfaction with the fit of their Level II body armor at the waist. The author followed up on these comments in a later (Barker, 2007) survey of 91 male officers, which revealed that 38% of the participating officers reported adjusting their vest at the neck or waist when the moved from a standing to a seated position. Other areas that may present fit issues include the underarms (Tung, 2008) and the shoulder (Fowler, 2003).

There are inconsistent findings in the current body of literature regarding how weight and shape of body armor may affect the comfort of the wearer. A limited number of studies are available that explore weight or shape of body armor. The existing research that has been published presents mixed conclusions of the relationship between weight and/or shape of body armor and wearer comfort (Barker et al., 2010; Barker & Black, 2009; Lee et al., 2013; Majchrzycka et al., 2013; Park et al., 2011).

**Body Armor Weight.**

The current research creates an unclear picture regarding the relationship between weight of body armor and comfort of the wearer. In two separate studies, participants were asked to complete tasks while wearing body armor of different weights. Both studies reported participants preferred the lightest weight body armor option (Barker et al., 2010; Majchrzycka et al., 2013). However, it is unclear from the existing literature how much change in weight of body armor is required to affect the wearer's comfort level (Barker et al., 2010; Marjchrazcha et al., 2013). The study by Majchrzycka et al. (2013) tested three types of body armor, weighing 2.10kg, 3.18kg and 2.40kg. A significant difference in wearer perceived comfort was found between the three types of body armor and was attributed to the weight change (Majchrzycka et al. 2013). Alternatively, Barker et al.'s study (2010) showed changing the weight of body armor by 0.20 oz./ft$^2$ was not a sufficient weight change to significantly affect wearer comfort.

The United States Department of Justice (US DOJ) acknowledges that weight of body armor affects comfort stating, "heavier body armor will increase the amount of fatigue an officer will experience" (2014, p. 22). Although this statement by the US DOJ is not linked to an empirical study, it is worth noting as it contributes to the ambiguity of how weight change in body armor may affect the wearers comfort.

**Shape and Design of Body Armor.**

The shape and design of body armor may affect the wearer's level of comfort (Barker & Black, 2009; Choi, Garlie, & Mitchell, 2009; Lee et al., 2013). However, more evidence is needed to develop a full understanding of how these factors can be manipulated to improve body armor comfort. Both Barker and Black (2009) and Lee et al. (2013) found that the wearer's comfort level was significantly influenced by design and bulkiness of body armor. Majchrzycka et al. (2013) maintained that shape had no significant effects on perceived comfort of the user. One reason for this may be the different levels of change made to the body armor in each study. For example, Lee et al.'s study (2013) conducted extensive preliminary research to undertake a complete redesign of the body armor carrier using 3D modeling technology. In this study, the standard body armor carrier was described by the author as 2-dimensional, meaning it lays flat when not being worn on the body. The experimental body armor carrier is described by the author as 3-dimensional, meaning it is molded to the body and cannot lay flat. The drastic change in design between the standard body armor carrier and the experimental body armor carrier may account for the significant change in wearer comfort (Lee et al. 2013). Majchrzycka et al. (2013) and Barker and Black (2009) took similar approaches in their change to body armor shape and design, with differing results. There is evidence to suggest that the reduction of bulk in the body armor shaping contributed to improved fit and coverage of the body armor studied (Choi et al., 2009).

**Wearer Perception of Comfort.**

No conclusion can be drawn about how the wearer's perception of comfort was affected by different types of body armor due to conflicting and ambiguous findings across the literature (Barker et al. 2010; Barker & Black, 2009; Majchrzycka et al., 2013). It is clear, however, that wearers feel less comfortable when wearing body armor as opposed to wearing no body armor (Caldewell et al., 2011; Dempsey et al., 2013; Lee et al., 2013; Ricciardi et al., 2008).

One concerning phenomenon is the evidence that users of body armor perceive the equipment as uncomfortable, even when there is no statistically significant change in the wearer's physical ability to complete tasks (Barker et al., 2010; Majchrzycka et al. 2013). Both Barker et al. (2010) and Majchrzycka et al. (2013) call for more research to explain the difference between physical ability and user perception.

As learned from the literature review, body armor is a protective garment designed to provide protection against specific ballistic threats within its coverage areas. While it offers necessary protection, it also presents adverse impacts of wearing it on one's physical, physiological, and psychological comfort. Moreover, lack of consistency in findings of previous studies urges further research, which justifies the rationale of this study.

# CHAPTER 3: METHODS

The methods for this study have been organized into three stages based on the model by LaBat and Sokolowski (1999). The goals of this research were to assess and improve the fit and comfort of a case company's body armor design. As the original model is designed to be versatile and worn with and without hard protective plates, it was tested under the two conditions for which it is designed. That is, throughout the study, the body armor was evaluated both with and without hard plates inserted. The case study approach adopted in this work allows for the fit and comfort of body armor to be researched in a contemporary and real world environment (Yin, 2014). An industry partner was selected and agreed to participate in the research inquiry. The details of our mixed methodology are summarized in the following sections, which will detail the selection of the case company, participant recruitment, the data collection procedures, data analysis procedures, and possible limitations of the methods adopted in this study.

## The Case Company

The case company is small to medium enterprise (SME) with fewer than 25 employees, located in the western region of the United States, which manufactures and designs a unique body armor solution for police officers. Fewer than two years prior to the start of this study, the case company launched a body armor division. The case company was chosen due to their interest in establishing a partnership with the research laboratory of the researcher. The company was still in the development and evaluation phase of the body armor products, which exhibited room for implementation of proposed design changes. Initial meetings with the case company revealed their interest in improving the fit and comfort of their body armor product, particularly because they have experienced an undesirable return rate of their original body armor product.

These early conversations also revealed the case company's well-developed relationships with their customer base, which would lend well to including the customers in the co-design process (Björgvinsson, 2008). The case company's needs aligned with the inquiry developed through the review of current literature, and the collaboration provided an opportunity to evaluate body armor fit and comfort in a real-world context.

**Participant Recruitment**

Participants included seven company employees (i.e., those who are already employed within the case company) and five product users (i.e., police officers from local stations). Police officers were chosen as specific users for this study because they are the primary customers of the case company and wearers of body armor. I referred to company employees as internal collaborators (ICs) and police offices as external collaborators (ECs). Both groups of participants were recruited to provide insight throughout all three stages of the co-design process.

Seven internal collaborators at the case company were identified as the appropriate representatives of the company, based on their job responsibilities to their body armor division of the company. To protect their privacy, detailed demographic information was not collected on the employees, although all were at least 18 years of age, and provided informed consent to participate. See Appendix A for the verbal recruitment and informed consent script approved by the Institutional Review Board (IRB) office of the researcher's university.

Understanding the needs of body armor users is critical in the assessment of the case company's body armor. External collaborators were eligible to volunteer based on the following inclusion criteria. External collaborators were required to be a) males, b) who are police officers, c) are at least 18 years old, d) have no history of musculoskeletal diseases, e) have experience wearing body armor on the job, and f) fit the case company's most popular size of body armor based on the company's sales history. The selected size of body armor is roughly equivalent to a male size X-Large. Five external collaborators were recruited as participants with the assistance of the case company using a purposeful sampling method. The case company forwarded an e-mail message from the researcher (approved by the IRB office of the researcher's university, see Appendix B) to existing customers who fit these criteria. Interested participants were asked to contact the researcher directly to schedule a visit to the laboratory where the experiment will be performed. External collaborators who volunteered were reimbursed for parking and mileage costs as well as incentivized with a product from the case company with a retail value of approximately $100.

## Data Collection Procedures

The three-stage process model (adapted from LaBat and Sokolowski, 1999) including Problem Definition and Research (stage 1), Creative Exploration and Evaluation (stage 2) and Implementation (stage 3) provides structure for the data collection procedures. Keeping with the objectives of co-design, employees and users were engaged during each of the three stages to contribute to the design process. Each of the following sections provides specific information about the types of data collected, and instruments used during each stage.

### Stage 1: Problem Definition and Research

The first phase of the research inquiry will include collection of perceived and experienced needs of the original body armor model from the employees of the case company as well as users of the body armor product.

**Needs of the case company.** Information was gathered about the needs of the case company through semi-structured interviews with internal collaborators. One-on-one interviews were conducted at the facilities of the case company (e.g., a small conference room). The goals of these one-on-one interviews were to understand the company's current fitting process as well as the employees' opinions and concerns about the current practice. Further, the interviews helped the researchers understand what the company has already done to attempt to improve the body armor previously, and the results of those attempts. The interviews were audio recorded and transcribed verbatim. A list of questions used to drive the conversation during case company interviews may be found in Appendix D. Probing was allowed to follow up with the participants when the researcher did not fully understand a response or wanted to obtain more in-depth information. Within this paper, quotations and comments from the interviews and focus group are not attributed to a specific collaborator. This was done to protect the privacy and identity of the collaborators due to the team-based, intimate nature of the company.

As a form of pilot data collection, two of the case company employees were interviewed in March of 2017 to assess the feasibility of collaborating on a research endeavor. The interview data from the pilot effort revealed the case company's concerns about the undesirable return rate on some male body armor products as previously mentioned in this document. The company believed that problems occur when the wearer goes from the standing to sitting position. They had previously addressed the problem that occurred during this activity where the body armor rises on the waist, and pushes up on the neck and back of the head. Another problem mentioned at the pilot interview regarding fit was occurring in the front of the chest, and under the arms. The fit and comfort at the neck, chest, waist, and arms were considered areas that needed further investigation in the first phase of research.

**Needs of product users.** To assess product users' needs, external collaborators were asked to visit the lab wearing their regular police uniform, including uniform pants, shirt, undershirt, shoes, duty belt, and other equipment. After providing informed consent (Appendix

C), the external collaborators were asked to participate in several activities during their visit to the lab. To address the company's customer needs related to physical and psychological comfort, I adopted mixed-methods including a survey, 3D body scanning, occupational task analysis with comfort ratings, and an exit interview.

***Survey questionnaire.*** A standard survey questionnaire developed and used by the research lab, titled the Human Body Dimensioning (HBD) Questionnaire (Appendix E), was administered to the study participants to collect their demographic and physical information (e.g., the participant's physical size, age, ethnicity, occupation history).

***3D body scanning.*** The 3D body scanning procedures, adapted from Park and Langseth-Schmidt (2016)'s study, were used to address the relationship between the garment and the body dimensions, as an aspect of the physical attributes of body armor comfort (Li, 2010). Prior to 3D scanning, participants received a short orientation of the scanning process, and their height and weight were measured using a stadiometer (Seca®) and a digital laboratory scale (TANITA® TBF-310). The participants were then asked to step in a private area located adjacent to the scanner, and change into undergarments for body scanning. When both the participant and the researcher were ready, the scanner provided audio instructions to the participant on the correct posture and stance for body scanning, and the participant initiated the scanning procedure by pressing a trigger on the side handlebars. This study used a stationary $[TC]^2$ KX-16® scanner with non-invasive depth sensors that capture a digital representation of the body using approximately 300,000 spatial data points per scan. Scanning was completed with the participants wearing four clothing ensembles utilizing the original model of the vest: 1) A baseline scan wearing only undergarments, 2) the body armor vest with soft panels inserted worn over a light athletic T-shirt, 3) the body armor vest with soft panels and hard plates inserted, worn over a light athletic T-shirt, and 4) The officers full uniform donned over the body armor vest with soft panels and hard plates inserted.

***Occupational task analysis.*** A Likert–type scale for rating subjective comfort was integrated with an occupational task analysis experiment to assess the perceived fit and comfort of users while wearing the body armor both with and without plates. During the occupational task analysis experiment, participants were asked to wear their regular uniform with the body armor being tested. This included their uniform shirt, pants, shoes and duty belt. The protocols for the occupational task analysis were adopted from Fowler's (2003) study, which was originally developed based on ASTM F1154-99 Standard Practices for Qualitatively Evaluating the Comfort, Fit, Function, and Integrity of Chemical-Protective Suit Ensembles. Based on the expertise of the case company, the list of tasks was modified from the original task analysis protocol by adding one additional task, i.e., drawing the shooting stance (as if using a firearm). These tasks, listed here (1-12), were meant to simulate the physical movements necessary for police officers wearing body armor on the job. The scale instrument for occupational task analysis with comfort ratings and along with further details on each task is attached in Appendix F. The set of tasks was performed by each participant while wearing the body armor both with and without plates, with a 10-minute rest period in between. With the participant's permission, the occupational task analysis portion of the lab assessment was be video- and audio-recorded.

1. Kneel on left knee, kneel on both knees, kneel on the right knee, stand. Repeat movement four times.
2. Duck, squat, pivot right, pivot left, stand. Repeat movement four times.
3. Stand erect. Extend arms over head, then bend elbows. Repeat movement four times.

4. Without using a firearm, simulate drawing the shooting stance, hold, and relax. Repeat movement 4 times. Repeat movement 4 times.
5. Walk a distance of 100 yards.
6. Crawl on hands and knees a distance of 20 feet.
7. Stand erect. Turn head to the left and return. Turn head to the right and return. Repeat movement four times.
8. Stand erect beside chair. Sit in chair. Return to standing position beside chair. Repeat four times.
9. Individually lift four boxes from the floor and place on a table. Return each box to the floor
10. Step up five stairs.
11. Climb up to the fifth rung of a ladder.

After each task, the participant was asked to rate their level of perceived comfort on a scale from 1 to 7, with 1 being extremely uncomfortable and 7 being extremely comfortable. This was assessed for overall comfort as well as comfort perceptions of the body armor around specific body parts including the neck, waist, and arms. Upon completion of all twelve tasks, participants were asked to rate their overall comfort using the same scale. Questions related to the overall comfort of the body armor have been adapted from those used by Barker in a 2007 study of Level II body armor. Prior to data collection, pilot testing of the occupational task analysis instrument was conducted with one peer and one case company employee to avoid confusing language and validate the instrument.

***Exit interviews.*** At the end of the assessment, participants were asked to respond to opened ended questions as well to allow them to provide comments about the comfort, fit and mobility they experienced while wearing body armor and completing the task. The comments during the occupational task analysis and at exit interviews allowed the researchers to understand the wearers' psychological perceptions of comfort (Li, 2010). The interview questions asked during the exit interview are attached in Appendix G. The interviews were audio recorded and transcribed verbatim for further analysis.

**Stage 2: Creative Exploration and Evaluation.**

The information from stage 1 was analyzed and used to inform stage 2, in which a prototype was developed with the objective of improving the fit and comfort of the body armor. The ideated results were consulted to the case company's development team, and feasibility of prototyping of the suggested design ideas was discussed. Internal and external collaborators provided feedback on the design ideas. One final design was selected and approved by the case company, and prototyped in one of the company's prototyping facilities. The fit and comfort of the prototype were evaluated and compared to the original model during stage 2 by repeating the assessment procedures from stage 1 (3D body scanning, occupational task analysis, and exit interviews) with external collaborators.

**Stage 3: Implementation.**

Upon completion, the lab testing results and recommendations developed from stages 1 and stage 2 were presented to the case company. Six company employees participated in a focus group at the case company's headquarters. These focus group questions can be found in Appendix H. Many of these internal collaborators had also participated in the stage one interviews at the company, although one participant was lost and one was replaced due to changes in employment or roles at the case company since the beginning of the project. The analysis and results of this inquiry are detailed in the following sections.

## Data Analysis

### Qualitative Data

Interviews with the case company employees and the user participants were transcribed verbatim for data analysis. The information from interviews was coded into emergent themes and subthemes using an open coding scheme, guided by Hsieh & Shannon (2005). The researcher, who is a graduate student, acted as the primary coder. When questions arose about the coding scheme, the student's academic advisor was consulted as a mentor and second coder. When needed, participants were offered the opportunity to read the findings and provide feedback to ensure that the researcher had an accurate understanding of what the interviewees meant to say, as a means of member checks (Tong, Saintsbury, & Craig, 2007).

### Quantitative Data

Quantitative data analysis was completed using RStudio Version 1.5.153. Descriptive statistics (mean, standard deviation) were calculated for demographic data. During stage 1, I performed paired samples t-tests to compare the comfort ratings of the occupational task analysis between the two wearing conditions of the original body armor model for all twelve tasks: body armor with and without plates across each task at the 95% confidence level. Pearson's Correlation tests were conducted using a holms adjustment to analyze the possible relationships among the body dimensions and the comfort ratings from the occupational tasks. A total of 2,470 correlation tests were performed but only significant relationships that informed our investigation are reported in the Results section. During stage 2, I performed paired samples t-tests to compare the comfort ratings for the occupational task analysis between the original model and the prototype model of the body armor vest (with and without plates). The following chapter (Chapter 4) is a manuscript which summarizes the first three chapters of this paper including the introduction, literature, and methods used. Additionally, the results, findings and conclusions of this data analysis are provided in Chapter 4.

# CHAPTER 4: MANUSCRIPT

## Introduction

In the current political and cultural climate, safety and physical protection are a concern for law enforcement officers, police departments, and those who outfit them with necessary safety garments. Since 2009, firearm assault has been a leading cause of death in law enforcement officers. Firearm assault kills more police officers than any job-related illness or non-vehicle related injury (National Law Enforcement Officers Memorial Fund [NLEOMF], 2018; U.S. Department of Justice, Federal Bureau of Investigation [US DOJ FBI], 2018).

Body armor is a garment worn by police officers to provide coverage and ballistic protection primarily to the wearer's torso (OLES USA, 2008). The use of body armor has been shown to substantially improve the likelihood of survival following ballistic impact within the coverage area as much as four times (LaTourette, 2010; Liu & Taylor, 2017b). In fact, it has been reported that since 1972, more than 3,000 police officers have been saved because they were wearing body armor when they encountered a ballistic threat (James, 2016).

Despite its protective benefits, officers may not use body armor, or may mis-use it even at great risk to their personal safety (Dunne & Smyth, 2007). Reports indicate that between 2007 and 2017, only 61% to 72% of the officers killed were wearing body armor at the time of death (NLEOMF, 2018; US DOJ FBI, 2018). Discomfort or improper fit contribute to officer's choosing not to wear body armor (Barker, 2007; Basich, 2008; Burton, 2018; Liu & Taylor, 2017a). Previous research affirms that wearing body armor is often an uncomfortable experience for the wearer (e.g. Barker, 2007; Barker & Black, 2009; Fowler, 2003). According to previous findings, wearing uncomfortable or ill-fitting body armor negatively affects the mobility, speed, and accuracy of physical tasks performed by police officers in the line of duty (Barker, 2007; Barker & Black, 2009; Dempsey, Handcock, & Rehrer, 2013; Fowler, 2003; Lee, Hong, Kim, & Lee, 2013). Furthermore, wearing body armor can result in lower back pain and injury because of the excess weight on the torso of the wearer (Burton, Tillotson, Symonds, Burke, & Mathewson, 1996; Larsen, 2018).

To gain practical insight into the discomfort police officers experience from wearing the body armor, we adopted a case study approach. The case company chosen for this research had evidence that customers were experiencing discomfort and fit issues with the original model of the company's body armor. This was causing an undesirable return rate of the product. The case company had need of investigation into the causes of the discomfort and reported fit issues, as well as recommendations and validation of technical design changes that would improve the problems. The case company's needs, along with contemporary issues of police officers' occupational injury and wearer resistance of body armor, encouraged this research effort. Furthermore, researchers urged the imperative nature of this research topic for occupational safety of police officers and the communities they serve (Barker & Black, 2009; Fowler, 2003; Park, Nolli, Branson, Peksoz, Petrova, & Goad, 2011). Thus, through this study, we aimed to identify the fit and comfort issues surrounding the case company's current body armor design, and suggest improvement in the technical design and fitting practices of the case company.

To achieve this research goal, we formulated the following specific research questions:

RQ1: What areas of the body interact with the body armor vest to influence the fit and comfort of the case company's body armor?

RQ2: How can the functional design elements of the body armor be manipulated to improve fit and comfort of the case company's body armor at the areas identified in RQ1?

The aforementioned research questions were investigated within the conceptual framework called co-design (Sanders & Stappers, 2008). Co-design is a democratic design paradigm that is based on the premise that 'users' are the experts of their own domain and should be actively involved in the design process. Specifically, we explored benefits of using the co-design philosophy in the university-industry collaboration project, which involved various stakeholders inside and outside the case company. Therefore, our last question was as follows:

RQ3: Does the co-design philosophy add value in product development process for a university-industry collaboration?

## Related Literature

### Types of Body Armor

The term 'body armor' refers to the personal protective garment worn by police officers that "provides protection against specific ballistic threats within its coverage area [and]… provides coverage primarily for the torso," (Office of Law Enforcement Standards & United States of America [OLES USA], 2008, p. 7). There are multiple components that make up the torso protection systems of body armor. The term 'carrier' will be used to refer to the vest garment that is worn to carry the protective materials on the body. Body armor is categorized into assigned levels based on the degree of protection and ballistic threats it can withstand (OLES USA, 2008). Level IIIA and Level III body armor will be discussed throughout this paper.

Level IIIA body armor is considered soft armor, meaning it is constructed from textile materials such as Kevlar®, Goldflex®, ArmorFelt®, Spectra®, or Dyneema® (Barker, Black, & Cloud, 2010; Barker & Black, 2009; OLES USA, 2008; United States Department of Justice [US DOJ], 2014). These soft materials are assembled into many layers and combined to create body armor ‘panels’. These panels are designed to be sewn or inserted into the carrier vest to provide ballistic protection. Level IIIA body armor is defined by its resistance to 357 SIG FMJ Flat Nose (FN) bullets with a specified mass of 8.1 g and a velocity of 448 m/s. and .40 S&W FMJ bullets with a specified mass of 11.7 g and a velocity of 325 m/s (OLES USA, 2008).

Level III body armor is considered ‘hard armor’ meaning it is constructed from rigid or semi-rigid materials such as ceramics, metals, laminates, or other composites (US DOJ, 2014). These materials are considered ‘plates’ and are meant to be inserted into the carrier vest to provide ballistic protection. Level III body armor is defined by its resistance to 7.62 mm FMJ, steel jacketed bullets with a specified mass of 9.6 g and a velocity of 847 m/s (OLES USA, 2008).

**The Adverse Effects of Wearing Body Armor**

The effect of wearing body armor (as compared to wearing no body armor) has been well documented in the existing body of literature. Findings suggest that wearing body armor may have negative effects on the wearer’s physical (Dempsey et al., 2013; Hasselquist, Bensel, Corner, Gregorczyk, & Schiffman, 2008; Park et al., 2011; Ricciardi, Deuster, & Talbot, 2008), physiological (Caldwell, Engelen, van der Henst, Patteson, & Taylor, 2011; Cheuvront, Goodman, Kenefick, Montain, & Sawka, 2008; Hasselquist et al., 2008; Montain, Sawka, Cadarette, Quigley, & McKay, 1994; Ricciardi et al., 2008) and psychological wellbeing (Caldwell et al., 2011; Majchrzycka, Brochocka, Łuczak, & Łężak, 2013). A brief overview of the key literature concerning the effects of body armor on the wearer is included here. Additional information and in-depth reviews of this topic may be found in several recently published meta-analyses (e.g. Joseph, Wiley, Orr, Schram, & Dawes, 2018; Larsen, Netto. &Aisbett, 2011; Schram, Hinton, Orr, Pope, & Norris, 2018; Tomes, Orr, & Pope, 2017).

**Physical.** Wearing body armor results in a reduction of the physical wellbeing of the wearer through reduced range of motion, physical performance, and stamina (Demsey et al., 2012; Hasselquist et al., 2008; Park et al., 2011; Ricciardi et al., 2008). Both upper and lower body mobility are negatively affected by wearing body armor (Dempsey et al., 2013; Hasselquist et al., 2008; Park et al., 2011). Pelvic intra-rotation, pelvic extra-rotation, pelvic anterior and posterior tilt were negatively affected when participants wore body armor as opposed to when they wore a tank top and athletic shorts (Park et al., 2011). Upper body mobility may be reduced by 13-42% when wearing body armor as measured through occupational physical challenges (Dempsey et al., 2013). Gait analysis shows significant changes in walking patterns for those wearing body armor, as opposed to wearing no body armor (Hasselquist et al., 2008; Larsen, 2018; Park et al., 2011). Wearing body armor results in the wearer exhibiting less range of motion when moving their feet forward (swing phase), their feet spend less time off the ground when moving forward (swing time), and they spend more time with both feet on the ground at the same time (double support time; Hasselquist et al., 2008; Park et al., 2011). Additionally, wearing body armor reduces the level of performance and stamina of the wearer in a variety of physical activities (Dempsey et al., 2013; Ricciardi et al., 2008). Both male and female military personnel experienced a significant reduction in the number of stairs they could climb per minute (Ricciardi et al., 2008). While male military exhibited a reduction in the number of pull-ups they could complete and a reduction in run-time before fatigue (Dempsey et al., 2013; Ricciardi et al., 2008), female military personnel were less able to hold their body weight while wearing body armor when compared to completing the same task without body armor (Ricciardi et al., 2008).

**Physiological.** It is well agreed upon, that wearing body armor has a negative effect on the physiological wellbeing of the wearer. By far, the most researched and well agreed upon topic is that wearers experience a significant increase in heartrate when wearing body armor, as opposed to wearing no body armor (Caldwell et al., 2011; Cheuvront et al., 2008; Montain, et al., 1994; Ricciardi et al., 2008). The increase in heartrate while wearing body armor is evident in a variety of environmental conditions (Caldwell et al., 2011; Cheuvront et al., 2008; Montain et al., 1994). There is less agreement on other physiological effects, but some evidence suggests that wearing body armor affects the wearer's oxygen consumption (Hasselquist et al., 2008; Ricciardi et al., 2008), sweat loss (Caldwell et al., 2011; Cheuvront et al., 2008), and blood lactate levels (Ricciardi et al., 2008).

**Psychological.** There is some conflicting evidence regarding the possible effect of wearing body armor on the psychological and cognitive wellbeing of the wearer (Caldwell et al., 2011; Majchrzycka et al., 2013; Roberts & Cole, 2013). Caldwell et al. (2011) reported that there was no meaningful change in cognitive function but Majchrzycka et al. (2013) and Roberts and Cole (2013) both reported that participants showed signs of mental fatigue after performing physical tasks in the body armor. This suggests that wearing body armor may have a negative effect on the wearer's psychological state (Majchrzycka et al., 2013, Roberts & Cole, 2013).

## Body Armor Fit and Comfort

Though a limited number of studies have investigated body armor fit and comfort, the neck and waist are considered the primary areas of concern (Barker, 2003; Fowler, 2003; Stubbs, Woods, & Beards, 2008; Tung, 2008) for both men and women. Discomfort around the neck has been characterized by a restriction or sensation of choking (Tung, 2008). Reshaping the neckline results in less protective coverage, but this change was considered preferable to the discomfort of the standard neckline by military women (Tung, 2008). A survey of 91 male police officers wearing Level II body armor indicated that 60.7% of the participating officers rated their vest was too tight around the neckline (Barker, 2007).

Multiple reports identify the waist area of body armor as ill-fitting or uncomfortable (Barker, 2007; Fowler, 2003; Stubbs et al., 2008; Tung, 2008). Dissatisfaction in the waist has been associated with sitting and standing. In a survey of 91 Florida police officers, 38% of the participating male officers reported adjusting their vest at the neck or waist when they moved from a standing to a seated position (Barker, 2007). Other areas of the body armor that may present fit issues include the underarms, (Tung, 2008), shoulders (Fowler, 2003) and hips (Stubbs et al., 2008).

It is generally accepted that increased body armor weight contributes negatively to the comfort of body armor (US DOJ, 2014), although it is unclear what magnitude of weight change is required to affect the wearer's comfort level (Barker et al., 2010; Fowler, 2003; Majchrzycka et al., 2013). However, the reduction of bulk seems to contribute to improved fit and coverage of body armor (Choi, Garlie, & Mitchell, 2019; Lee et al., 2013).

No clear conclusion can be drawn about how the wearer's perception of comfort was affected by different types of body armor due to conflicting and ambiguous findings across the literature (Barker et al. 2010; Barker & Black, 2009; Majchrzycka et al., 2013). It is clear, however, that wearers feel less comfortable when wearing body armor as opposed to wearing no body armor. One concerning phenomenon is the evidence that users of body armor perceive the equipment as uncomfortable even when there is no statistically significant change in the wearer's physical ability to complete tasks (Barker et al., 2010; Majchrzycka et al., 2013). This suggests additional research.

## Theoretical Frameworks

### Co-design

This study was guided by the philosophy of co-design. Co-design (sometimes used interchangeably with collaborative design or participatory design) can be characterized by involving various stakeholders in the design process (Sanders & Stappers, 2008). This includes bringing traditional designers, researchers, businesses, and users of the product to the table to explore ideas and possibilities (Fuad-Luke, 2009). There is no standard model or process for co-design. Rather the co-design methodology has been envisioned differently by various scholars and is generally viewed as a flexible design paradigm (Visser, Stappers, van der Lugt, and Stappers, 2005).

Through co-design, stakeholders are given new roles meant to nurture collaboration. The researcher acts as a facilitator among the parties and guides them to participate in the design process (Sanders & Stappers, 2008). Internal collaborators are those within the case company (i.e. employees) and those outside the case company (i.e. users, customers, or potential customers) are referred to as external collaborators (Morris, 2011). In the co-design context, internal and external collaborators should be considered experts of their own experiences regarding product use and their needs related to the product (Sanders & Stappers, 2008). The role of the external collaborator may be as a resource, co-creator, product tester, or a combination of these (Morris, 2011; Nambisan, 2002). The designers are responsible for bringing the ideas of the collaborators to life (Sanders & Stappers, 2008; Visser et al., 2005). It has been suggested that designers should also strive to take on different roles (i.e. facilitator) throughout the process to better understand the various perspectives of collaborators in the co-design process (Lee, 2008).

Co-design has been established as a method for generating successful prototypes both when developing physical tools and virtual systems. (Visser et al., 2004; Björgvinsson, 2008). It has been suggested that collaboration, especially for prototype development is most successful when the collaborators establish a long-term relationship (Björgvinsson, 2008).

**Three-Stage Process for Product Development**

After a broad review of potential process models, a three-stage product development process was adopted to organize and drive the current research inquiry. The Three-Stage Design Process by LaBat and Sokolowski (1999) was developed to guide the collaboration between industry partners and university students. The process outlines the following three stages to successful product development: 1) Problem Definition and Research, 2) Creative Exploration and Evaluation, and 3) Implementation (LaBat & Sokolowski, 1999). During the Problem Definition and Research stage it is suggested that the design problem be assessed from the client's perspective to define user and market needs. The identified needs should also be assessed to create a working problem definition (LaBat and Sokolowski, 1999). The Creative Exploration stage is described as the least defined stage in the model by LaBat and Sokolowski (1999). It is recommended that the researcher begin by exploring all the possibilities for solving the design problem. Only after all possibilities have been explored, the design ideas are refined. The refined ideas are then implemented into a prototype. The third stage, Implementation, involves the case company working with the researcher to implement the recommendations into their product development process. LaBat and Sokolowski (1999) specifies that implementation may be done in multiple phases if time or cost prevent the case company from making changes all at once.

**Integrative Process Model Used in This Study**

Co-design was the overarching philosophy guiding the study, with the three-stage process model (LaBat & Sokolowski, 1999) used to organize the implementation of co-design into the product development investigation. The diagram in Figure 4.1 displays our proposed integration of these two strategies. Strategies and methods for co-design are embedded in each stage of the process. The first stage, *Problem Definition and Research*, incorporates input from the internal and external collaborators to determine the needs of the case company and product users respectively. These needs are evaluated to define the research and problems to be investigated in the *Creative Exploration and Evaluation* stage (stage 2), where all possible solutions to the design problems are explored based on the collaborators' inputs. In this stage, prototypes are developed and evaluated with internal and external collaborators. Finally, in stage 3, *Implementation*, the outcomes from stages 1 and 2 are discussed and internal collaborators develop plans for short term and long term implementation of the final recommendations.

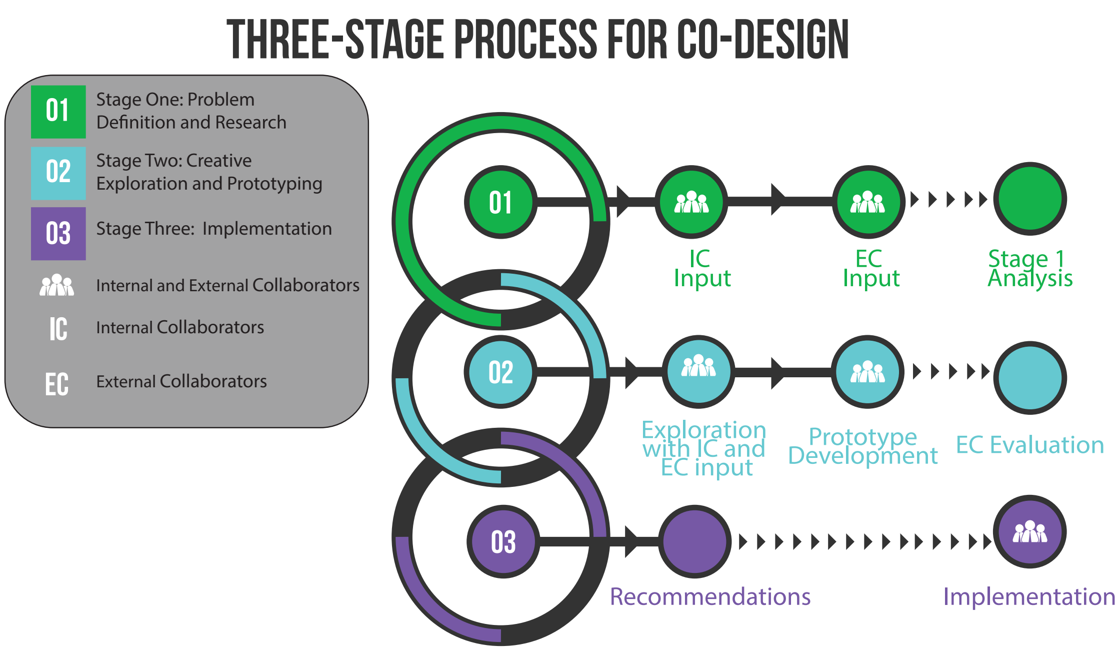


***Figure 4.1:*** *Integrative Process Model*

# Methods

## The Case Company

The case company is a small to medium enterprise (SME) with fewer than 25 employees, located in the western-region of the United States, which manufactures and designs a unique body armor solution for police officers. Fewer than two years prior to the start of this study, the case company launched a body armor division. The case company was chosen due to their interest in establishing a partnership with the university research laboratory of the researchers. The partnership was ideal because the company was still in the development and evaluation phase of the body armor products, which exhibited room for implementation of proposed design changes. Initial meetings with the case company revealed the company was experiencing an undesirable return rate of the body armor. Customers were reporting discomfort and fit issues during the return process. These early conversations also revealed the case company's well-developed relationships with their customer base, which would lend well to including the customers in the co-design process (Björgvinsson, 2008). The case company's needs aligned with the inquiry developed through the review of current literature and provided the opportunity to evaluate body armor fit and comfort in a real-world context.

## Participant recruitment

We recruited seven company employees (i.e., those who are already employed within the case company) and five product users (i.e., police officers from local stations). Police officers were chosen as specific user for this study because they are the primary customers of the case company and wearers of the body armor. Both groups of the participants acted as collaborators in the co-design process. We referred the company employees as internal collaborators and police officers as external collaborators (Morris, 2011).

Seven internal collaborators were identified as the appropriate representatives of the company based on their job responsibilities to the case company. To protect their privacy, detailed demographic information was not collected on the employees, although all were at least 18 years of age, and provided informed consent to participate. The external collaborator group was eligible to volunteer based on the following inclusion criteria. Users were required to be (1) males, (2) who were police officers (3) were at least 18 years old, (4) had no history of musculoskeletal diseases, (4) had experience wearing body armor on the job, and (5) fit the case company's most popular size of body armor based on the company's sales history (approximately men's X-Large). Five police officers were recruited with the assistance of the case company using a purposeful sampling method. The case company helped the recruitment effort by forwarding an e-mail message drafted by the researcher (approved by the Institutional Review Board (IRB) of the researchers' university) to the company's existing customers who fit these criteria. Participants who volunteered were reimbursed for parking and mileage costs as well as incentivized with a product donated by the case company with a retail value of $100.

**Stage 1: Problem Definition and Research**

One-on-one interviews with the internal collaborators were conducted in a private room at the case company's facilities. These were semi-structured interviews with questions being used to drive the conversation. Probing was allowed in all interviews as a means to increase the trustworthiness of the data. The objective was to define the project scope, allowing the researchers to understand the product history and the case company's future goals regarding the product. The case company also provided detailed technical information about their product and sizing system to assist the researchers in their understanding of the product. Within this paper quotations and comments from the interviews and focus group are not attributed to a specific collaborator. This was done to protect the privacy and identity of the collaborators due to the team-based, intimate nature of the company.

To assess product users' needs, external collaborators were asked to visit the lab wearing their regular police uniform, including uniform pants, shirt, undershirt, shoes, duty belt, and other equipment. After providing informed consent, participants were asked to complete a short demographic survey, participate in 3D body scanning, an occupational task assessment with comfort ratings, and an exit interview. The 3D body scanning was used to collect the participants baseline body dimensions with a [TC]2, KX-16® that uses non-invasive depth sensors to capture a digital representation of the body using approximately 300,000 spatial data points per scan. During the occupational task assessment, participants were asked to perform 12 physical tasks under two clothing conditions: body armor with and without hard plates inserted. The original model of the case company's body armor was provided and used in the lab during stage 1 of the research. For the first condition, participants donned their clothing in the following layers. 1) undergarments including underpants and an undershirt 2) the body armor vest with soft panels and hard plates inserted 3) regular uniform pants and shirt, 4) duty belt and other equipment, 5) regular uniform socks and shoes. For the second condition, all the clothing remained the same except in layer 2 the body armor vest was worn with soft panels but without the hard plates inserted. After each task, the participant was asked to rate their level of perceived comfort on a scale from 1 to 7, with 1 being extremely uncomfortable and 7 being extremely comfortable. This was assessed for overall comfort as well as comfort perceptions of the body armor around specific body parts including the neck, chest, waist, and arms. The protocols for the occupational task analysis were adapted from Fowler's (2003) study and ASTM Standard F1154-99. Based on the expertise of the case company, the list of tasks was modified from the original task analysis protocol by adding one additional task, i.e., drawing the shooting stance (as if using a firearm). These tasks, listed in Table 4.1, were meant to simulate the physical movements necessary for police officers wearing body armor on the job.

***Table 4.1:*** *Tasks for Occupational Task Analysis*

| Task Name | Task Description |
|---|---|
| Kneeling | Kneel on left knee, kneel on both knees, kneel on the right knee, stand. Repeat movement four times. |
| Ducking and squatting | Duck, squat, pivot right, pivot left, stand. Repeat movement four times. |
| Reaching above head | Stand erect. Extend arms over head, then bend elbows. Repeat movement four times. |
| Shooting stance | Without using a firearm, simulate drawing the shooting stance, hold, and relax. Repeat movement 4 times. |
| Reaching across body | Stand erect. Reach arms across chest completely to opposite sides. Repeat movement 4 times. |
| Walking | Walk a distance of 100 yards. |
| Crawling | Crawl on hands and knees a distance of 20 feet. |
| Head movement | Stand erect. Turn head to the left and return. Turn head to the right and return. Repeat movement four times. |
| Standing and sitting | Stand erect beside chair. Sit in chair. Return to standing position beside chair. Repeat four times. |
| Lifting and lowering boxes | Individually lift four boxes from the floor and place on a table. Return each box to the floor |
| Climbing stairs | Step up five stairs. |
| Climbing ladder | Climb up to the fifth rung of a ladder. |

Upon completion of all twelve tasks participants were asked to rate their overall comfort using the same scale as the assessment of comfort for individual tasks. Participants provided open-ended comments throughout the procedure and a short exit interview was conducted to capture the participants' opinions of the fit and comfort of the body armor.

### Stage 2: Creative Exploration and Evaluation

The information from stage 1 was analyzed and used to inform stage 2, in which a prototype was developed with the objective of improving the fit and comfort of the body armor. The ideated results were consulted to the case company's development team, and feasibility of prototyping of the suggested design ideas was discussed. After a low fidelity prototype was assembled, internal and external collaborators provided feedback on the design ideas. One final design was selected and approved by the case company, and prototyped in one of the company's prototyping facilities. The fit and comfort of the prototype were evaluated and compared to the original model during stage 2 by repeating the assessment procedures from stage 1 (3D body scanning, occupational task analysis, and exit interviews) with external collaborators.

### Stage 3: Implementation

Upon completion, the lab testing results and recommendations developed from stage 1 and stage 2 were presented to the case company. Six company employees participated in a focus group at the case company's headquarters. Many of these internal collaborators had also participated in the stage one interviews at the company, although one participant was lost and one was replaced due on changes in employment or roles at the case company since the beginning of the project.

## Data Analysis

Quantitative data analysis was completed using RStudio Version 1.5.153. Descriptive statistics (mean, standard deviation) were calculated for demographic data. During stage 1, we performed paired samples t-tests to compare the comfort ratings from all twelve tasks of the occupational task analysis between the two wearing conditions of the original body armor model: body armor with and without plates across each task at the 95% confidence level. Pearson's Correlation tests were conducted using a holms adjustment to analyze the possible relationships among the body dimensions and the comfort ratings from the occupational tasks. A total of 2,470 correlation tests were performed. During stage 2, we performed paired samples t-tests to compare the comfort ratings for the occupational task analysis between the original model and the prototype model of the body armor vest. Only significant relationships and/or those that informed our investigation are reported in the Results section. Qualitative data was coded into emergent themes and subthemes using an open coding scheme, guided by Hsieh & Shannon (2005). The first author, who is a graduate student, acted as the primary coder. When questions about the coding scheme arouse the second author, the student's academic advisor, was consulted. When needed, participants were offered the opportunity to read the findings and provide feedback, as a means of member checks (Tong, Saintsbury, & Craig, 2007). Member checks were used primarily with the case company employees to ensure that the researcher had an accurate understanding of what the interviewees meant to say.

## Results

### Participant Profiles

The internal collaborators worked in roles at the company including sales, design, management, and marketing. Detailed demographics of the internal collaborators were not collected in order to protect the identity of the participants within their company. However, to help readers understand the general characteristics of the participants, basic demographics are presented in Table 4.2. The mean (SD) age of external collaborators (i.e., police officers) was 38.2 (10.57) years old. On average, they reported wearing their body armor for 171.6 (48.71) total hours per month. Further demographic information for the external collaborators can be found in Table 4.3.

***Table 4.2:*** *Description of Internal Collaborators*

| Internal Collaborator ID | Job role at company | Stage 1 interview | Stage 3 focus group |
|---|---|---|---|
| 1 | Industrial Design | X | X |
| 2 | Product Development | X | X |
| 3 | Marketing | X | |
| 4 | Marketing | X | |
| 5 | Sales | X | X |
| 6 | Sales | X | X |
| 7 | Sales | X | X |
| 8 | Management | | X |

***Table 4.3:*** *Demographics and Body Dimensions*

| | Average (SD) | Details |
|---|---|---|
| Age | 38.2 (10.57) | Age in years at the start of the study |
| Time in body armor | 171.6 (48.71) | Hours wearing their body armor vest per month as reported by the officers. |
| Height | 71.05 (2.59) | Total body length in inches, top of the head to floor. |
| Weight | 231.44 (20.60) | Weight in pounds (lbs.) measured using a TINITA scale. |

## Stage 1: Problem Definition and Research

**The case company's perspective.** The case company's body armor product is a modular design that allows the wearer to adjust the level of protection by adding and removing plates and panels. The versatility of the product contributes to the brand's place at the top of the market. However, the unique armor solution may be contributing to the undesirable return rate, as it complicates the fit and sizing process. Internal collaborators revealed that the company was committed to producing top-of-the line protective gear that acted as a solution to everyday problems that their customers (police officers) face regarding their body armor. As stated, the company was experiencing an undesirable return rate and one of the key company objectives was to reduce the return rate by improving the fit and comfort of the product. The company had made some changes prior to this collaboration and were interested in continuing to make changes to improve fit, comfort, and sizing.  Employees of the company saw a benefit to research-based product development and were generally in favor of participating in the co-design process. In fact, the company was already developing strong relationships with their customers. In addition to product design changes, they were also open to improving the system changes at the company.

**Product user needs assessment.** In this section, we will present a summary of notable findings from comfort ratings of the occupational task analysis, and the quantitative findings were supplemented by the exit interview narratives.

***Comfort ratings of occupational task analysis.*** Of the twelve tasks, the lowest rated for overall comfort were shooting stance, ducking and squatting, lifting and lowering boxes, and reaching across the body (Table 4.4). Images of these four tasks can be found in Figure 4.2.

***Figure 1.2:*** *Photos of four critical tasks: ducking and squatting (top left); shooting stance (top right); reaching across the body (bottom left); lifting and lowering boxes (bottom right).*

Shooting stance was rated lowest of the twelve tasks for overall comfort when the original model was worn with plates (mean = 4.10 sd = 1.245), and without plates (mean = 6.00, sd = 0.00) and showed a difference (mean difference = 1.90, sd = 1.245) that was statistically significant at the 95% confidence level (p = 0.027). Of the specific body parts that caused the feeling of discomfort, chest and arms seemed to be the body areas most affected by the shooting task. The comparison showed a mean rating of 3.40 (sd = 1.342) for comfort around the chest when worn with plates, and a mean of 5.50 (sd = 0.500) when worn without plates. The difference between these two conditions (mean difference = 2.10, sd = 1.432) for comfort around the chest while drawing the shooting stance was statistically significant at the 95% confidence level (p= 0.031). The comparison showed a mean rating of 4.60 (sd = 1.950) for comfort around the arms with plates and 6.10 (sd = 0.548) without plates when drawing the shooting stance. This mean difference between the two conditions (mean = 1.50, sd =1.80, p =0.14) was not statistically significant.

When considering the difference in overall comfort of ducking and squatting while wearing the original body armor with plates (mean 5.10, sd = 0.652) versus without plates (mean = 6.80, sd = 0.447), there was a mean difference of 1.70 (sd= 0.758) between the two conditions which was statistically significant (p = 0.007). Of the specific body parts that caused the feeling of discomfort, arms and waist seemed to be the body areas most affected by ducking and squatting. When ducking and squatting, the difference between the two conditions for comfort around the arms (mean difference = 1.20, sd = 1.789, p= 0.208) was greatest, though not statistically significant. There was no difference between the two conditions for comfort around the waist (mean = 5. 80).

Comparing the comfort ratings for lifting and lowering boxes with plates (mean = 5.10, sd = 0.742) versus without plates (mean = 6.20, sd =0.84) showed a mean difference of 1.10 (sd = 0.894, p = 0.051) for overall comfort of the task. Of the specific body parts that caused the feeling of discomfort, waist seemed to be the most affected by lifting and lowering boxes. When lifting and lowering boxes, the differences between the two conditions for comfort around the waist (mean difference = 1.40, sd = 0.894) was found to be statistically significant (p = 0.025).

Analysis of the ratings for overall comfort when reaching across the body showed a mean rating of 5.40 (sd = 1.817) when plates were worn and a mean of 6.40 (0.894) without plates. This estimated mean difference of 1.00 (sd = 1.414) for overall comfort between the plated and non-plated conditions was not statistically significant (p = 0.189). Of the specific body parts that caused the feeling of discomfort chest (mean = 5.8, sd = 1.789) and arms (mean = 5.5, sd = 1.871) seemed to be the areas most affected by reaching across the body with plates. When reaching across the body, the difference between the two conditions was greatest for comfort at the arms (mean = 1.50, sd = 1.871, p = 0.178) although it was not statistically significant.

### ***Table 4.4:*** *Comfort Ratings for Key Tasks*

| Task | Body Area Rated | Original Vest | | | | Prototype Vest | | Prototype versus Original Vest | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No Plates | Plates | Plates vs No Plates | Plates vs No Plates | No Plates | Plates | No Plates | Plates | No Plates | Plates |
| | | Mean (SD) | Mean (SD) | Mean (SD) | p-value | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | p-value | p-value |
| Shooting stance | Overall | 6.00 (0.000) | 4.10 (1.245) | 1.90 (1.245) | 0.027* | 6.600 (0.548) | 5.100 (1.342) | 0.600 (0.548) | 1.00 (0.354) | 0.075 | 0.003** |
| | Chest | 5.500 (0.500) | 3.40 (1.342) | 2.10 (1.432) | 0.031* | 6.600 (0.548) | 5.800 (0.837) | 1.100 (0.742) | 2.400 (1.673) | 0.029* | 0.033* |
| | Arms | 6.100 (0.548) | 4.600 (1.949) | 1.500 (1.803) | 0.136 | 6.800 (0.447) | 6.000 (1.000) | 0.700 (0.975) | 1.400 (2.510) | 0.184 | 0.280 |
| Ducking and squatting | Overall | 6.800 (0.447) | 5.100 (0.652) | 1.700 (0.758) | 0.007** | 6.800 (0.447) | 6.500 (0.500) | 0.000 (0.00) | 1.400 (0.962) | | 0.031* |
| | Arms | 7.000 (0.000) | 5.800 (1.789) | 1.200 (1.789) | 0.208 | 6.800 (0.447) | 6.500 (0.500) | -0.200 (0.447) | 0.600 (0.894) | 0.374 | 0.208 |
| | Waist | 5.800 (0.837) | 5.800 (1.789) | 0.000 (1.581) | | 6.700 (0.447) | 6.600 (0.548) | 0.900 (0.742) | 0.800 (1.924) | 0.053 | 0.405 |
| Lifting and lowering boxes | Overall | 6.200 (0.837) | 5.100 (0.742) | 1.100 (0.894) | 0.051 | 7.000 (0.000) | 6.400 (0.548) | 0.800 (0.837) | 1.300 (0.671) | 0.099 | 0.012* |
| | Waist | 6.200 (0.837) | 4.80 (0.837) | 1.40 (0.894) | 0.025* | 6.900 (0.224) | 6.800 (0.447) | 0.700 (0.975) | 2.00 (1.225) | 0.184 | 0.022* |
| Reaching across body | Overall | 6.400 (0.894) | 5.400 (1.817) | 1.000 (1.44) | 0.189 | 7.000 (0.000) | 6.500 (0.500) | 0.6000 (0.894) | 1.100 (2.012) | 0.208 | 0.289 |
| | Chest | 6.200 (1.304) | 5.800 (1.789) | 0.400 (0.548) | 0.178 | 6.950 (0.112) | 6.900 (0.224) | 0.750 (1.346) | 1.100 (1.884) | 0.281 | 0.262 |
| | Arms | 7.000 (0.000) | 5.500 (1.871) | 1.500 (1.871) | 0.147 | 7.000 (0.000) | 6.800 (0.447) | 0.000 (0.000) | 1.300 (1.987) | | 0.217 |

Note:
* denotes p-values ≤ 0.05    ** denotes p-values ≤ 0.01    *** denotes p-values ≤ 0.001

***Correlations body dimensions with comfort ratings.*** To further explore the areas of the body that were most affected by wearing body armor, 3D body scan data was explored in its possible relationship to comfort ratings. Nine key body measurements were determined based on the information from the literature review and case company knowledge: the height, center front (CF) length, center back (CB) length, waist circumference, chest circumference, neck circumference, upper arm circumference, hips and the circumference of the armscye. The results of Pearson's correlation tests revealed that the length of the torso (CF and CB), chest circumference and waist circumference were the most influential body measurements in their relationship to the comfort ratings reported during the occupational task analysis. As seen in Table 4.5, torso length and waist circumference showed trends toward a negative correlation to subjective comfort while chest circumference showed a trend toward a positive correlation with the comfort ratings for several tasks. That is, as the torso length and waist circumference increased, the comfort ratings generally decreased. On the other hand, as the chest circumference increased, the comfort ratings increased at several tasks performed.

***Table 4.5:*** *Correlation Table of Body Measurement & Comfort Ratings for Occupational Task Analysis.*

| **Body Measurement** | **Task** | **Body Area Rated** | **Plates Yes/No** | **R-value** | **P-value** |
|---|---|---|---|---|---|
| Center Back | Reaching above head | Arms | No | -0.982** | 0.018 |
| | Shooting stance | Arms | No | 0.892* | 0.042 |
| | Reaching across body | Chest | No | -0.978** | 0.004 |
| | | | Yes | -0.934* | 0.020 |
| | | Overall | No | -0.934* | 0.020 |
| | Walking | Arms | Yes | -0.982** | 0.003 |
| | Crawling | Waist | No | -0.934* | 0.020 |
| | Overall | Chest | No | -0.982** | 0.003 |
| | | Neck | Yes | -0.982** | 0.003 |
| | | Overall | No | -0.982** | 0.003 |
| Center Front | Kneeling | Overall | No | -0.850* | 0.043 |
| | Ducking and squatting | Overall | No | -0.934* | 0.013 |
| | Reaching above head | Arms | No | -0.907* | 0.022 |
| | Reaching across body | Chest | No | -0.915* | 0.019 |
| | | | Yes | -0.850* | 0.043 |
| | | Overall | No | -0.850* | 0.043 |
| | Walking | Arms | Yes | -0.934* | 0.013 |
| | | Overall | Yes | -0.934* | 0.013 |
| | Crawling | Waist | No | -0.850* | 0.043 |
| | Overall | Chest | No | -0.934* | 0.013 |
| | | Neck | Yes | -0.934* | 0.013 |
| | | Overall | No | 0.934* | 0.110 |
| Chest circumference | Reaching above head | Neck | No | 0.913* | 0.030 |
| | Crawling | Arms | No | 0.897* | 0.039 |
| | | Neck | Yes | 0.913* | 0.030 |
| | Sitting and standing | Waist | No | 0.945* | 0.015 |
| | Lifting & lower boxes | Arms | No | 0.913* | 0.030 |
| | Climbing stairs | Arms | No | 0.913* | 0.030 |
| Waist circumference | Kneeling | Waist | No | 0.894* | 0.041 |
| | | | Yes | -0.928* | 0.023 |
| | Reaching across body | Overall | Yes | -0.920* | 0.027 |
| | Ducking and squatting | Overall | No | -0.918* | 0.028 |

*Note: * denotes p-values ≤ 0.05 ** denotes p-values ≤ 0.01 *** denotes p-values ≤ 0.001*

***Open ended comments.*** The participant's responses to the open-ended questions revealed that they felt the most discomfort in the chest during tasks where they were required to bring their arms forward in front of the body as when drawing the shooting stance or to a lesser degree, when reaching forward to lift boxes and reaching across the body. This discomfort was noted by one participant, "It just seems uh, binding through here [inner arms where they meet the chest]. …it's kind of squeezing, preventing me from getting a good lock up" and was generally described as a "pinching" or "rubbing" where the arms and chest meet the body armor. Participants also disclosed that discomfort in the waist was experienced during tasks where they were required to bend forward or 'crunch' at the waist (as when lifting and lowering boxes). This discomfort was discussed by one external collaborator when "[the vest] got lifted up a little bit, and it was pinching a little bit [at the waist] when I was picking the [boxes] up…" and was generally regarded as a restriction or a pinching in the abdomen. Outside the conversation of comfort and fit, external collaborators discussed department policy and budget as factors that affect their adoption of body armor.

***Propositions developed from stage 1.*** Based on the results detailed in this section it was determined that the critical areas of the body affected by discomfort were the waist, chest, and underarm area. Improving the comfort in these areas was determined to be the most critical need of the external collaborators. Thus, we developed five propositions (refer to Figure 4.3). Through the subsequent creative exploration stage, these propositions were leveraged into design changes and evaluated for their effectiveness.

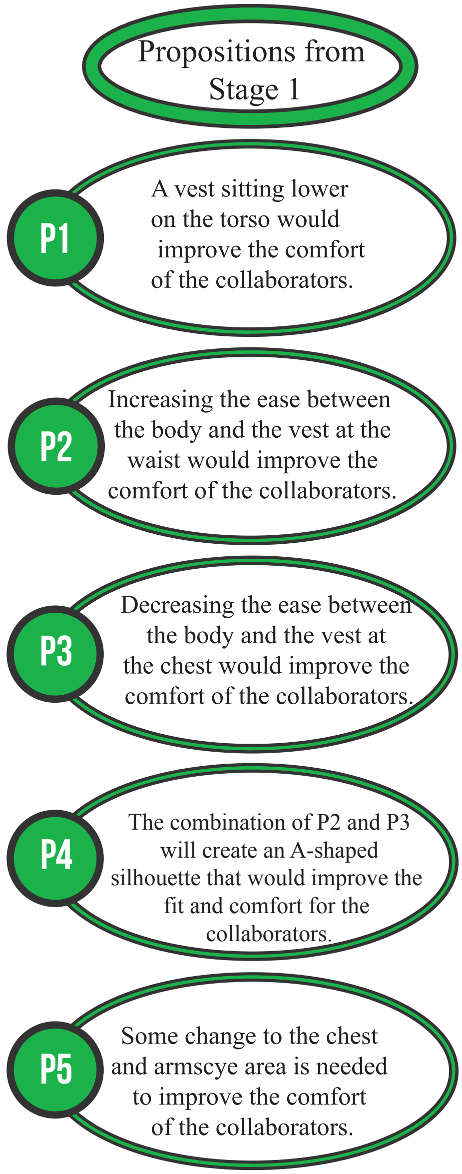


***Figure 4.3:*** *Propositions developed from stage 1*

**Stage 2: Creative Exploration and Evaluation**

**Prototype Development.** The information presented in stage 1 was discussed with internal collaborators to generate several suggestions for the development of a new prototype. After reviewing the results and brainstorming possible solutions, we narrowed the list to the best possible solutions. First, a low fidelity prototype was developed. Internal and external collaborators gave input on the first prototype. Based on this feedback, the design details were finalized and a fully finished prototype was developed through the company's normal manufacturing channels. The changes made in the new design were visualized in Figure 4.4 and details were summarized in Table 4.6. With the design changes in the prototype finalized, the propositions developed in stage 1 were refined, as described in Figure 4.5.

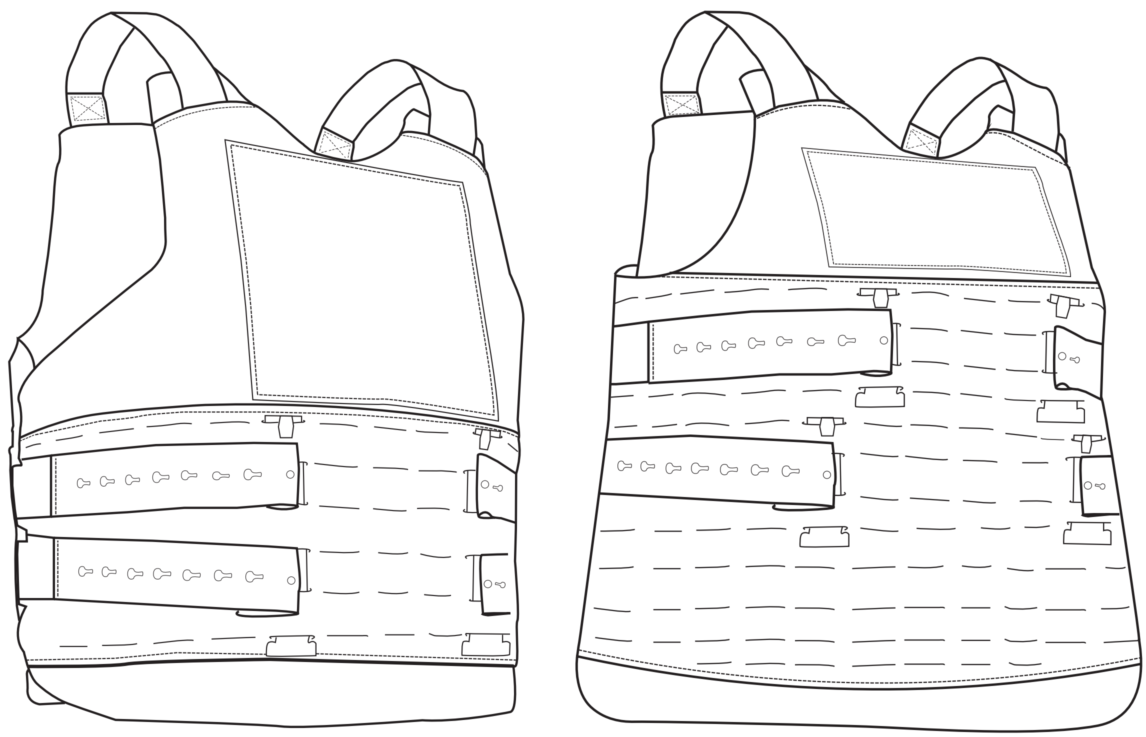

***Figure 4.4:*** *Comparison of original (left) and prototype (right).*

*Table 4.6:* *Changes from Original to Prototype Model.*

| Body Area | Changes from original to prototype | Justification for change |
|---|---|---|
| Torso Length | • Lengthened 1" at hem (center front, center back). | • Many negative correlations between torso length and subjective comfort.<br>• Descriptive data of torso length. |
| Chest area | • Reshaped chest and armscye to curved underarm shape.<br>• Brought the side seam up into underarm area about 1.5 inches, improving comfort.<br>• Raised closure system at both side seams to secure around lower part of chest, and at natural waist. | • Low subjective ratings for chest area.<br>• Open ended comments.<br>• Demographic data of chest level and armscye. |
| Chest circumference | • Reduced circumference of chest area in the vest by about 4 inches. | • Positive correlation between chest circumference and comfort ratings.<br>• Descriptive data of chest circumference. |
| Waist circumference | • Increased circumference of waist area in the vest by about 4 inches. | • Negative correlation between waist circumference and comfort ratings. |
| Other | • Plastic composite plates buffed with a smooth rounded edge.<br>• Increased coverage of pals and MOLLE field.<br>• Raised closure system to lower chest and natural waist.<br>• Offset the anchor points on closure system for added adjustability. | • Comments from external collaborators.<br>• New practice at the case company (internal collaborators).<br>• To facilitate chest and waist design changes.<br>• Allows for independent fit of the waist and chest. |

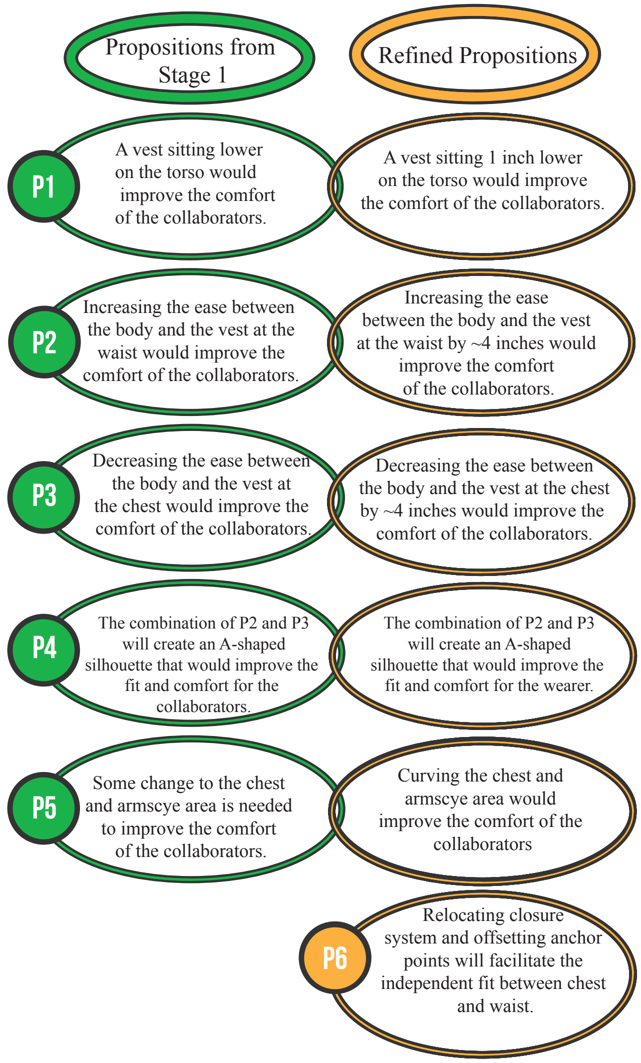


***Figure 4.5**: Refined propositions.*

**Prototype Evaluation.** The external collaborators' evaluation of the prototype confirmed that the following tasks were most influential to comfort: drawing the shooting stance, lifting and lowering boxes, ducking and squatting, and reaching across the body. These tasks showed an improvement in comfort when the prototype vest was worn, as compared to the original vest. Details of the comfort ratings from the occupational task assessment are found in Table 4.4 and Figure 4.6.

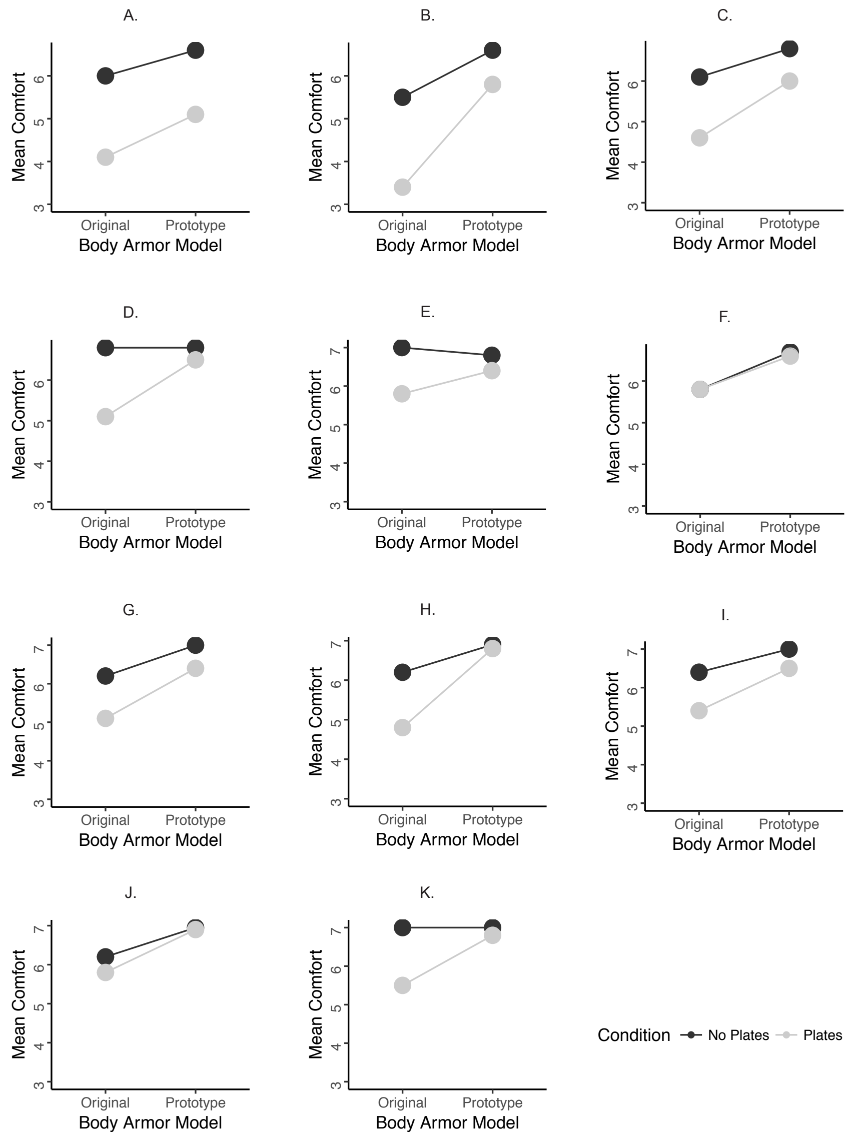


***Figure 4.6:*** *Mean Comfort Rating Comparisons. A) Overall comfort of the shooting stance, B) Comfort in the chest for the shooting stance, C) Comfort in the arms for the shooting stance, D) Overall comfort of ducking and squatting, E) Comfort in the arms for ducking and squatting, F) Comfort in the waist for ducking and squatting, G) Overall comfort of lifting and lowering boxes, H) Comfort in the waist for lifting and lowering boxes, I) Overall comfort of reaching across the body, J)Comfort in the chest for reaching across the body, K) Comfort in the arms for reaching across the body.*

Comfort ratings for overall comfort of the shooting stance show a statistically significant improvement during the plated condition with a mean difference of 1.00 (sd = 0.354, p = 0.003) when the prototype is compared to the original model. A statistically significant difference in comfort ratings was also found for comfort around the chest while drawing the shooting stance with plates (mean difference = 2.40, sd = 1.673), p = 0.029) and without plates (mean difference=1.10, sd = 0.742 , p = 0.033) when wearing the prototype as compared to wearing the original body armor model. There was a mean improvement rating of 1.40 (sd = 2.510) in the comfort around the arms when drawing the shooting stance while wearing plates in the prototype as opposed to the original model, although it was not statistically significant (p = 0.280).

Comfort ratings for ducking and squatting show a statistically significant improvement in overall comfort (p = 0.031) when plates are worn with the prototyped body armor as compared to the original body armor model. There was an improvement in the participants' mean comfort around the arms (mean improvement = 0.60, sd = 0.894, p = 0.208) when plates were worn, as well as in the waist both with plates (mean improvement = 0.800, sd = 1.987, p = 0.217) and without plates (mean improvement = 0.900, 0.742, p = 0.053) although the differences were not statistically significant.

Comfort ratings for lifting and lowering boxes show a statistically significant mean improvement (mean = 1.30, sd = 0.671) for overall comfort (p = 0.012) and comfort around the waist (mean = 2.00, sd = 1.225, p = 0.022) when plates are worn with the prototyped body armor as compared to the original body armor model.

Comfort ratings for reaching the across the body, show a mean improvement of 1.10 (sd = 2.012) when plates were worn with the prototyped body armor as compared to the original model, although the difference was not statistically significant (p = 0.289). The comfort around the chest (mean improvement of 1.10, sd = 1.884, p = 0.262) and arms (mean improvement = 1.300, sd = 1.987, p = 0.217) also improved when reaching across the body while wearing plates with the prototype as compared to the original model, although the difference was not statistically significant.

**Participant qualitative assessment.** Subjective comments were captured throughout the occupational task analysis scenarios, as well as during the exit interviews. These comments revealed the curved armscye and the A-shaped silhouette were well received. Other changes saw mixed reviews, and the participants did not favor the change in the length of center back. Many of the participants did not immediately notice all the changes to the vest. To better facilitate a discussion of these changes, the exit interviews included the participant doffing the vest and viewing the original model and the prototype model side by side.

***Chest area.*** Overall, the participants experienced an improvement in the comfort around the chest and arms, especially when bringing their arms forward. Although they did still feel some discomfort in this area, it was considered as less painful or distracting than in the original model. As one participant stated the prototype was "not cutting into me as much" in the chest area. Participants did feel like the prototype was very rigid, and explained that they thought the comfort could be further improved if they had time to "break in" the vest.

***Curved chest and underarm area.*** All the participants had positive and favorable comments regarding the change in the armscye shape and additional coverage. Only one participant noticed the change on his own, while the others were surprised to see such a drastic increase in coverage when they viewed the prototype and original model side-by-side. This pleasant surprise was attributed to the fact that they did not feel more bulk or material under their arms. As one participant described "Ultimately, I think the way that you've curved this out [pointing at the curved and raised armscye] is probably the best thing you could've done because having it higher up in the armpit, um, …that's [previously exposed area] how most officers die." According to the participant, a local officer had recently encountered an unexpected ballistic threat. Although the officer was wearing body armor, he was hit by a bullet in his exposed underarm area and was ultimately killed due to these injuries. The curved shape of the armscye is found to be a successful modification as all the officers were interested in increasing coverage and protection, and this change had no negative affect on their mobility or comfort.

***Length of body armor on torso.*** Most of the participants did notice the added length to center front and center back of the vest. Participants did agree that the added length at center back was unfavorable and described this as too long, sticking out, or negatively interacting with their duty belt at center back. While officers were sometimes hesitant to discourage a change that included extra coverage, they experienced better comfort in the length of the original vest.

***Waist area and closure system.*** Overall external collaborators seemed to favor the idea of additional shaping in the silhouette of the vest. Some participants noted that an A-shape of the prototype would not be right for every body shape and a V-shape might be considered for those whose chest measurement is larger than their waist measurement. Participants felt that the waist was now too wide. If the A-shape was going to work, the waist change would be less drastic. Some external collaborators did note that the modified closure system might take more time to adjust, but admitted these adjustments would be needed infrequently. Overall the external collaborators liked the added adjustability provided by the offset anchor points.

***Overall.*** When asked, most of the participants felt that they would prefer to wear the prototype vest over the original vest. Even the participants who were unsure explained that with a longer wear test, they might have a chance to 'break in' the prototype potentially making it the more comfortable option. Overall participants had a positive opinion regarding the prototype. As one participant explained "… it's an improvement over [the original model], it is". While another confirmed that he felt the design changes were "going in the right direction".

**Propositions developed from stage 2.** Data from the prototype evaluation in stage 2 was used to draw the following conclusions about our propositions (Figure 4.7), and shape our final recommendations to the case company.

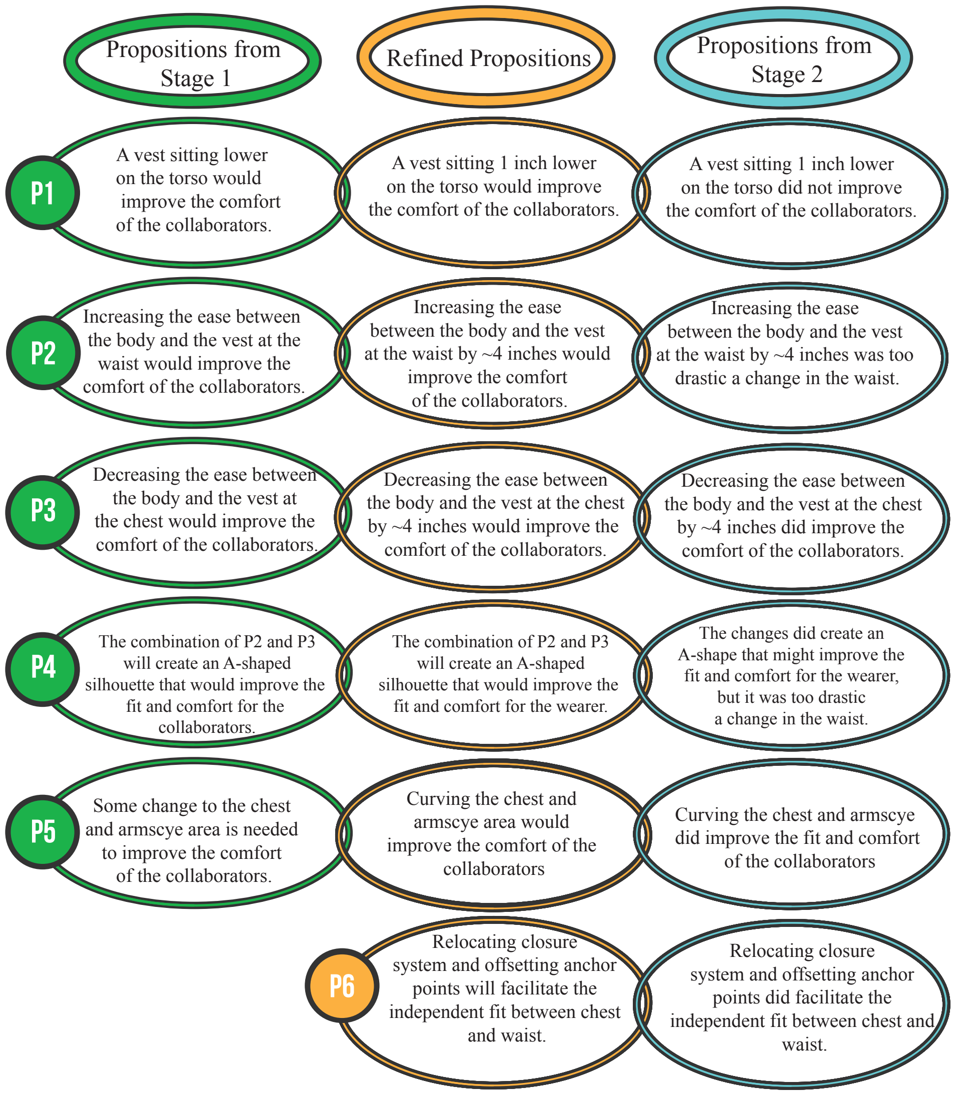


***Figure 4.7:*** *Propositions developed from stage 2.*

The comfort ratings from the occupational task analysis showed an improvement in the task that involved bending or crunching at the waist (lifting and lowering boxes) both with and without plates. However, due to the negative subjective assessment surrounding the added length of the vest it was recommended that the case company should not take this modification to market.

The comfort ratings showed an improvement in the task that involved bending or crunching at the waist (lifting and lowering boxes) both with and without plates. There is still evidence that a looser fit in the waist improves the comfort of the wearer. However, the subjective assessment surrounding the waist circumference suggested that the increase of four inches as too large. It was recommended that the case company consider a less drastic change to the waist circumference if they wanted to explore this change in their product line. The comfort ratings showed major improvements in the comfort of the tasks that involved the chest area (shooting stance and reaching across the body). There is evidence that the comfort around the chest was improved by reducing the chest circumference. This change was supported by the positive subjective assessment from external collaborators. It was recommended that the case company reduce the ease between the body and the vest at the chest area in their main product line. However, it was also noted that the amount of ease would differ for each size of the company's product. Based on conclusions drawn about the waist (P2 in Figure 4.7) and chest areas (P3 in Figure 4.7) an A-shape silhouette is recommended for the population studied, although it should be less drastic than the prototype. It was recommended that the case company explore additional shaping options that would accommodate different body shapes.

The comfort ratings showed major improvements in the comfort of the tasks that involved the chest and underarm area. This change was highly supported by the positive subjective assessment from external collaborators. It was recommended that the case company implement the curved armscye into their product (P5 in Figure 4.7).

Based on the subjective assessment from the external collaborators. It was recommended that the case company implement some adjustment to the closure system (P6 in Figure 4.7). The location of the top strap of the closure system at the lower chest level (as in the prototype, See Figure 4.8) is recommended. However, it is recommended that the bottom strap of the closure system be moved below the natural waist (as opposed to the natural waist, as in the prototype). Offsetting the placement of the anchor points of the closure system is also recommended.

**Stage 3: Implementation**

The findings and recommendations presented in stage 2 were delivered to the case company to inform a focus group with internal collaborators. Plans were developed for implementation at the product design level and the company system level. Themes emerged regarding specific design changes, sizing and shaping of the product, product development and evaluation tools, and the use of co-design for product development.

**Product design changes.** A focus group with the internal collaborators revealed that a new product model was being developed which would include recommendations from this study. The new product was schedule to launch within six months of this study's completion, giving time for further internal evaluation and implementation planning within the company. The recommended body armor design, as compared to the original and prototyped design can be seen in Figure 4.8.

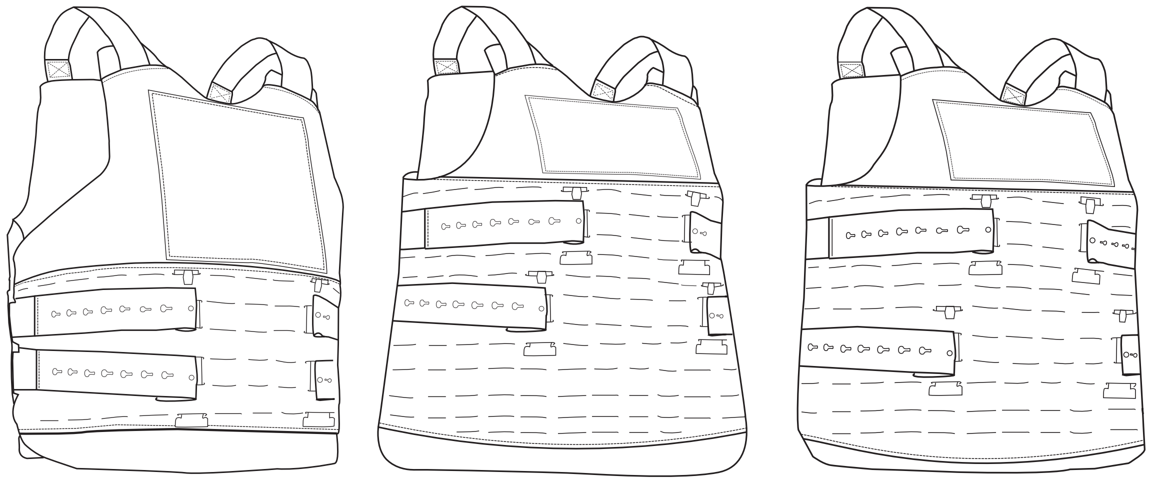

***Figure 4.8:*** *Original (left), prototyped (center),*

*and recommended designs (right).*

As recommended, the company did not change the length of the body armor from their original design. The reduction of chest circumference and the curved armscye were considered the most important improvements in the prototype. As noted by an internal collaborator:

> I think the biggest take away from this is the chest circumference. You know, because that is something we see and hear a lot about, you know so, implementing that is definitely so- one of our main priorities right now. Um, you know, the curve … maximizes coverage [and that] is good.

There was some discussion about how the curved armscye might interact with other design changes the company had planned for the new prototype (outside the scope of this study) but curved shape was considered a high priority. Plans were developed to implement the reduced chest circumference and curved armscye into the new product model.

When discussing the increased waist circumference and A-shaped silhouette, the company was hesitant to move too quickly. It was determined that a less dramatic change might contribute to an improvement in comfort, but it might not be right for all body types. There was some debate among internal collaborators if a less drastic A-shape should be implemented immediately or if more research was needed. One internal collaborator stated, “so I mean like, probably wanna test that out before you go throwing ‘Hey, A-shape’s better than the barrel’ ” while another collaborator noted “one of things I keep going back to, there was more thought put into the [A] shape versus the initial shape… which leads me to believe you know, I’m more inclined to trust this”. In the end, it was decided that the company would put a focus on investigating this idea through internal testing before making a decision about implementation.

Changes to the closures system were discussed, but the company wanted to further investigate before drawing conclusions about implementation. Some internal collaborators saw a benefit to offsetting the anchor points of the closure system an asked if it could be implemented “right away”. However, another collaborator noted that there might be a large cost involved, and wanted to first explore the cost-benefit ratio. The discussion of modifying the placement of the closure system (top strap at chest level, bottom strap below natural waist) drew no immediate conclusions, but the company was open to exploring the idea in the future.

**Company system changes.** When considering the use of the research methods in this study, the company saw a benefit of our mixed methods approach including the use of 3D body scanning and the occupational task analysis.

***Shaping and sizing.*** The company did not see any issue with implementing the reduction in chest circumference or the curved armscye into the product without modifying their current sizing system. As described by one collaborator, “I don't see any issue with the sizing system being affected from how we're, …how you characterize the body in those points that we're taking it off the body in order to build their vest”. The company was also open to future discussions that would create more shaping options such as offering an A, V, or H shape silhouette for each size or a fully custom make-to-measure sizing system. These ideas were considered long-term considerations and this discussion lead to the topic of 3D body scanning detailed in the next section.

***Product development and evaluation tools.*** The company thought it would be ideal if they could use a portable 3D body scanner to automate a fully custom made-to-measure product line. As one participant explained:

> Now, like I said, we try to it in to an automated process, it's not a problem, right if I can, you know, like I said, scan somebody or just hit measurements and plug it in and it's good to go based off of these measurements, we'd love to do that. Um, you know, we'll probably look at looking at doing that.

The company plans to investigate this option in the future. However, this was considered appropriate for a long-term change. Because the company provides body armor to police departments across the country, a portable scanning system was considered necessary. The present technology exists, but involves a time and cost burden considered too large for immediate implementation.

The company planned to immediately implement an adapted version of the occupational task analysis and comfort ratings into their prototype development process. At the time of the focus group, the researchers provided recommendations on use and modification of the occupational task analysis and the associated survey instrument that could benefit the case company. The case company quickly implemented this into their next phase of internal prototype testing. Field testers (national police officers) in various sizes were given a prototype vest in their size. They were asked to complete a modified occupational task analysis, and fill out the associated survey with Likert-type scales. The modified prototype included the suggested changes to the curved armscye, and a less drastic A-shape silhouette than that in the initial research prototype. The team expressed plans to continue using these testing methods internally for future product development as in a comment from one collaborator, “here's how we validate a change, guess what, we get these guys in, we have to do these tasks…we've got the base line now of, you know, we can repeat it”.

**Co-design and university-industry collaboration.** Overall the collaboration was viewed as a successful endeavor by both the researchers and case company employees. It was revealed that this thorough evaluation would not have occurred without the collaboration: “we wouldn’t have been able to devote all of the resources that you spent doing this, I mean, it’s nothing but a benefit to us”. Both the researchers and company were agreed that the co-design process was beneficial as it allowed us to compare and align the views of users, employees, and researchers. This was expressed by internal collaborators when they said “instead of being like, oh we've got feedback from these guys, its like, well no, it was a true collaboration, you know, … its- its real, you know, and that has a huge impact”. In another comments like “you can see some eyebrows raised from like, certain individuals that [saw the]… prototypes” and “the nice thing too is, you know, in the end, from your side, your work is not in vain, right.” Internal collaborators saw the benefit beyond their company and noted that the researchers, and external collaborators gained agency through the experience.

**Overall perceptions.** The internal collaborators stated they had made strides toward reducing their return rate since the start of the study, and that these design changes would help further resolve their undesirable return rate. “I feel like we've … reduced our return rates, you know-…Especially with the implementation of this, I believe so”. They were also pleased that our findings aligned well with the feedback they had recently received from customers as evidenced by comments like “One thing that I was very impressed with looking at all this is, even though still a small sample, it seems like a lot of stuff here you guys found was stuff that we're seeing in real life.” Finally, the collaboration was seen as beneficial to their product design, and their brand position as they promote “winning by design” and this collaboration helped them to “push that [innovative design] on all fronts”.

## Discussion

In this study, we have identified that the waist, chest, and underarm are the critical areas of the body that interact with body armor to influence fit and comfort. By developing and testing a prototype vest, we have pinpointed specific solutions for manipulating the functional design of the body armor to improve the comfort and fit in those areas. The use of co-design in the product development process was found to be a valuable philosophy for guiding a university-industry collaboration. Discussion related to our three research questions is detailed in this section. The key points of our study are summarized in the context of the three-stage process for co-design (see Figure 4.9).

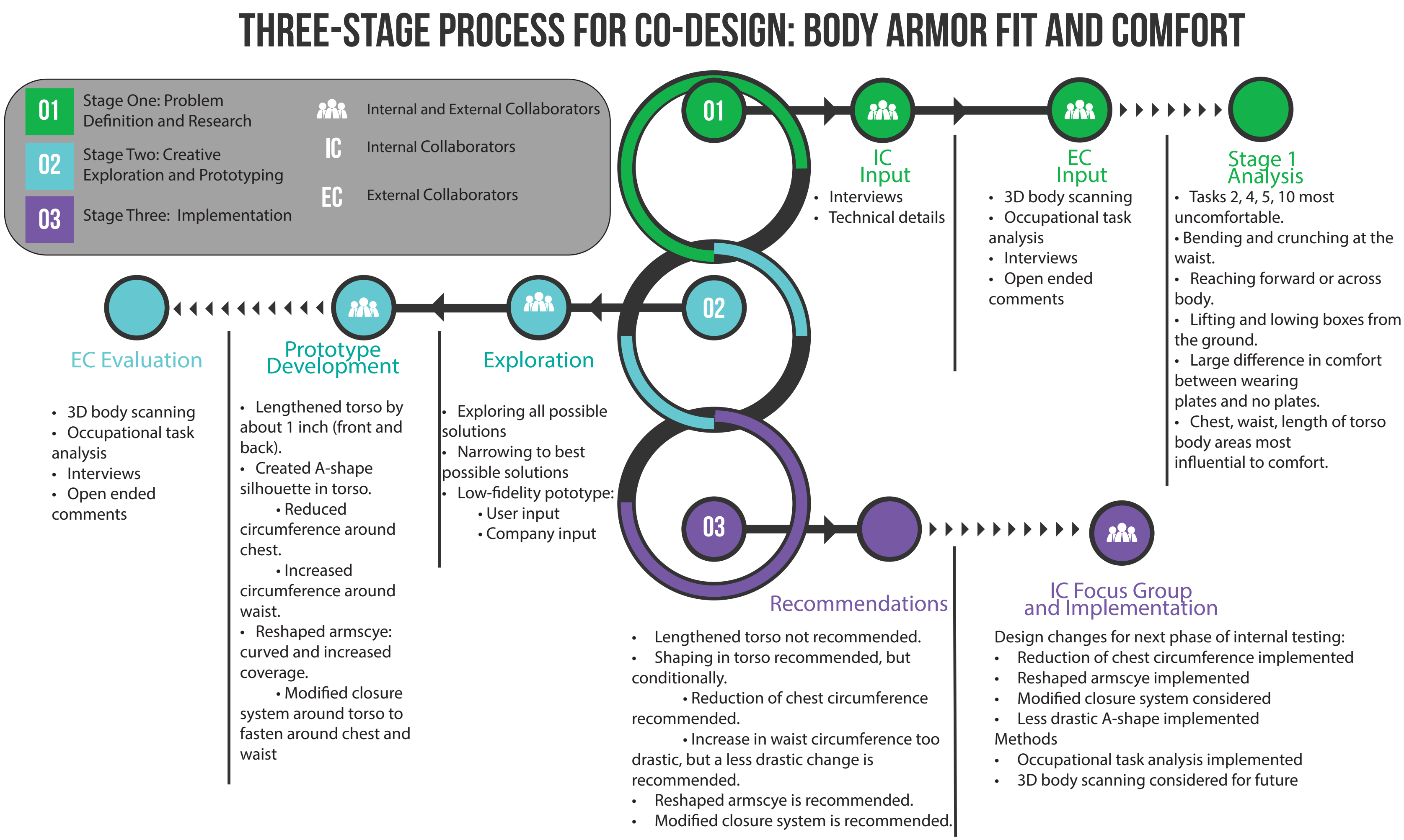


***Figure 4.9:*** *Integrative Process Model for Body Armor Fit and Comfort*

RQ1: What areas of the body interact with the body armor vest to influence the fit and comfort of the case company's body armor?

The chest, underarm, and waist were found to be key areas that influenced the comfort and fit of the body armor. The identification of the underarm and waist are in line with findings from previous research (Barker, 2007; Tung, 2008). Our findings also indicated the interaction of the body and the vest at the chest heavily affected comfort, which corresponded with previous research (Barker, 2007; Fowler, 2003). Unlike Barker (2007) and Tung (2008), we found little evidence of significant discomfort in the shoulders and neck area caused by wearing body armor. This may be attributed to the fact that the case company carefully considered the neck and shoulders when designing the original model as these are known problem areas. In addition to changes in the pattern and structure of the body armor, we found that placement and adjustability of the closure system contribute to the fit and comfort of body armor.

RQ2: How can the functional design elements of the body armor be manipulated to improve fit and comfort of the case company's body armor at the areas identified in RQ1?

This study concluded that fitting the vest more snugly and securely around the chest improved the comfort of the wearer, which expanded on previous research (Barker, 2007; Fowler, 2003). Similar to Stubbs et al. (2008), we found that fit and comfort around the chest and waist were independent factors. A good fit in the chest area did not mean a good fit around the waist, or vice versa.  This is like findings that encourage tighter fitting body armor as it decreases bulk and increases coverage (Choi et al., 2019; Lee, 2013).  The curve shape we implemented to the chest and armscye of the body armor was based on the understanding of the shape of the body, and the implemented changes increased body coverage and perceived comfort, thus improving the safety of police officers. This is in line with the recommendations from Choi et al.

(2019) to reshape the armscye for this purpose. While there is still evidence in the present study that a vest with a loosely fitting waistline improved the comfort of the wearer, the ideal amount of ease in the waistline was undetermined. Additional research is needed to determine the ideal amount of ease that should be included in the waist of the vest

Our findings suggested the placement of the vest on the torso was influential to wearer comfort. However, our research could not conclude exactly what manipulation produced the ideal fit and comfort in this area. The fit of the body armor at the waist is a complex issue that involves the qualities of the body armor itself as well as possible interactions with the duty belt (Barker, 20007), other garments (Barker, 2007; Stubbs et al., 2008), and the near environment (Stubbs et al., 2008). More research is needed to determine additional factors that may affect the fit and comfort of the body armor, especially as it pertains the length of the vest and the length of the wearer's torso.

The changes to the waist closure system added only slightly to the actual flexibility and adjustability of the vest, but they were well received by the external collaborators. We speculate that the staggered attachment system on the prototype increased the discoverability of this feature (Norman, 2013).

RQ3: Does the co-design philosophy add value in product development process for a university-industry collaboration?

The inclusion of users and company experts as collaborators throughout the co-design process was a successful structure for investigation throughout this study. Policies and budget of the local police departments emerged as additional considerations for body armor development. Keeping with the goals of bringing all stakeholders to the design process, future studies may benefit from including police department administrators to the co-design process when studying body armor (Sanders & Stapper, 2008). The inclusion of administrators would allow for a discussion concerning the policies regarding external versus internal vests, which was a concern discussed by officers in this study as well as previous studies (Grant et al., 2012).

Participants without a design background were sometimes hesitant to offer suggestions. As was done in other studies, it is recommended that future studies employ additional activities such as workbooks, sketching, post-cards or other ideation methods to evoke ideas from participants in the co-design process (Björgvinsson, 2008; Demirbilek & Demirkan, 2004; Sanders & Stappers, 2008).

**Limitations and Suggestions for Future Research**

The findings of this study are somewhat limited by geographic region, gender, and occupation due to the purposeful sampling method and a small sample size collaborating in the co-design process. While purposeful sampling is a non-probability sampling method, it may introduce bias into the study because there is no guarantee that the sample is representative of the larger population (Wolverton, 2009). This study was designed as a single case study, investigating only one size of body armor. Therefore, more research is needed to evaluate how these findings affect other sizes and designs of body armor. Future research may benefit from investigating the fit and comfort needs of female police officers who wear body armor on the job as they may differ from those of their male counterparts. A study comparing geographic regions is encouraged for future researchers as findings could vary by climate, culture, or environmental conditions (Barker, 2007). This study focused on police officers as the users of body armor, but comparisons with other occupations will also be important for future research. There is some evidence to suggest that other first responder occupations such as firefighters and EMS technicians may request or be required to wear body armor for their occupational safety (Krebs, 2014).

The case company's adoption of the occupational task analysis with subjective comfort ratings will allow them to further validate our findings. Those who seek to use this method are encouraged to make the following adaptions to the occupational task analysis: 1) In addition to sitting and standing from a desk chair it is recommended that participants practice getting into and out of their patrol vehicle (Derafshi et al., 20017; Stubbs et al., 2008). 2) If testing could take place at a police station or firing range it would be preferable to adapt the shooting stance task to including drawing the firing stance and discharging the firearm.

While 3D scanning and subjective comfort perceptions were assessed based on anthropometric fit of the body armor, objective measurement of range of motion (ROM) was beyond this study's scope. Future researchers are encouraged to consider the use of a motion capture system, and/or biological feedback (heart rate, body temperature, sweat rate) in addition to capturing the subjective assessments of comfort.

## Conclusions

Despite the considerations discussed, this research has contributed to the knowledge surrounding body armor fit and comfort. The findings of this study have identified key body areas and body armor attributes that influence the fit and comfort of the protective garment. The use of co-design was assessed for its value in the product development process. The design and system recommendations given here are expected to improve the case company's product and process, as well as reduce returns related to issues of fit and comfort. On a larger scale, the lessons learned from this study were anticipated to provide insightful guidance for other manufacturers and stakeholders in solving fit and design problems associated with body armor, with a hope to lower human factors barriers in adopting the protective shield among police officers.

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# APPENDIX A: CASE COMPANY VERBAL RECRUITMENT AND CONSENT

**VERBAL RECRUITMENT/CONSENT Body Amor Recruitment (case company employees):**

In conversational style, …

Hello, my name is Brittany Conroy and I am a graduate student researcher from Colorado State University in the Design and Merchandising Department. We are conducting a research study on the fit and comfort of body armor. The title of our project is "Analysis of Body Armor Fit and Comfort Using 3D Body scanning: A Case Study with an Industry Partner". The Principal Investigator is Dr. Juyeon Park with the Department of Design and Merchandising and I am the Co-Principal Investigator.

We would like you to take part in a semi-structured interview and a focus group. Participation will take approximately one to two hours for each interview or focus group. Your participation in this research is voluntary. With your permission, we would like to audiotape the interviews. Only the researchers will have access to the audiotapes, and they will be destroyed once they are transcribed. If you decide to participate in the study, you may withdraw your consent and stop participation at any time without penalty.

Would you like to participate?

If yes: Proceed.

Do we have your permission to audiotape the interview?

If yes: Proceed.

If no: Thank you for your time.

We will not collect your name or personal identifiers. When we report, and share the data with others, we will combine the data from all participants. There are no known risks or direct benefits to you, but we hope to gain more knowledge on the fit and comfort of the case company's body armor product. Whether you participate in this study or not will have no impact on your job status.

I will give you a sheet with the contact information for myself, Dr. Park, and the contact information for the office of Participant's Rights at Colorado State University. If you have any questions about your rights as a volunteer in this study please contact CSU's IRB office.

# APPENDIX B: PRODUCT USER E-MAIL RECRUITMENT SCRIPT

Hello__________________,

I am Brittany Conroy, a graduate student at Colorado State University in the Department of Design and Merchandising. I am working with Dr. Juyeon Park, in the Human Factors Product Innovation Laboratory at CSU. Our research lab is collaborating with the team at [redacted] to conduct a research investigation titled "Analysis of Body Armor Fit and Comfort Using 3D Body Scanning: A Case Study with an Industry Partner". We are reaching out to you because of your personal experience with the product. We are seeking volunteer participants who:

- Are male.
- Are at least 18 years old.
- Are a law enforcement officers.
- Have experience wearing body armor on the job.
- Wear roughly a male size X-large shirt.
- Have no history of muskuloskeletal disease.

The purpose of this study is to identify and improve the fit and comfort of [redacted] body armor. If you agree to participate, you will undergo a series of research procedures ranging from 3D body scanning, task analysis and a short interview. The 3D body scanning uses noninvasive depth sensors to measure the dimensions of your body. The task analysis will include completing physical tasks and motions while wearing body armor. These tasks are basic, and designed to represent your daily activities. Examples of these tasks include walking 100 feet, climbing up and down 5 steps, and moving from a standing to seated position. During the task analysis, you will be asked questions about your comfort and the comfort and fit of the body armor.

If you chose to participate, you will have a commitment to visit CSU twice over the period of the study. The first visit should be scheduled for September or October of 2017. The second visit should be scheduled for January or February of 2018. Each visit will take approximately 2-3 hours. As a participant, you will be compensated with an [redacted] for your time and efforts. You will also be reimbursed for mileage and parking fees incurred while visiting the lab at CSU. While there is no direct benefit to you, your participation will enhance occupational safety of law enforcement officers by improving the fit and comfort of the body armor worn while on duty.

Thanks for your time and consideration. If you have any questions or would like to be a participant, please contact me at Britt.Conroy@colostate.edu or call (906)360-9249 to schedule a time for your first visit to our lab at Colorado State University.

Thank you,

Brittany Conroy
Graduate Student and Research Assistant
Colorado State University
Britt.Conroy@colostate.edu

Dr. Juyeon Park
Associate Professor
Colorado State University
Juyeon.Park@colostate.edu

# APPENDIX C: PRODUCT USER WRITTEN INFORMED CONSENT FORM

**Consent to Participate in a Research Study (User assessment)**
**Colorado State University**

**TITLE OF STUDY: Analysis of Body Armor Fit and Comfort Using 3D Body Scanning: A Case Study with an Industry Partner.**

**WHY AM I BEING INVITED TO TAKE PART IN THIS RESEARCH?** You were recruited as a study participant because of your previous experience wearing body armor on the job. You meet the following inclusion criteria. You are:

- Male.
- At least 18 years old.
- A current law enforcement officer.
- Who has experience wearing body armor on the job.
- Who wears roughly a male size X-large shirt.
- Who has no history of muskuloskeletal disease.

**PRINCIPAL INVESTIGATOR:** Juyeon Park, Ph.D., PI, Associate Professor, Department of Design & Merchandising, Colorado State University, Juyeon.Park@colostate.edu
**CO-PRINCIPAL INVESTIGATOR:** Brittany Conroy, Graduate Research Assistant, Department of Design & Merchandising, Colorado State University, Britt.Conroy@colostate.edu

**WHO IS DOING THE STUDY?**
The researchers of the Human Factors Product Innovation Laboratory at Colorado State University will conduct this study in partnership with [redacted] to learn more about the fit and comfort of company's body armor product.

**WHAT IS THE PURPOSE OF THIS STUDY?** The overall purpose of this study is to identify and improve the fit and comfort issues surrounding a case company's current body armor design. By improving the fit and comfort of the body armor, this research aims to reduce the high number of products returned to the case company, as well as provide a more wearable product for law enforcement officers.

**WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?** The user needs assessment will take place in the Human Factors Product Innovation Laboratory, located in the Gifford Building (room 141) at Colorado State University. The total duration of the time commitment is expected to be 2-3 hours per session, with two sessions (a total of 4-6 hours for each participant).

**WHAT WILL I BE ASKED TO DO?** If you decide to join this study, you will be asked to visit the Human Factors Lab two times to participate in a laboratory assessment of body armor. During your first visit, you will be asked to complete a short questionnaire that asks questions about your basic demographic and physical information. Your height, weight, and body mass index will be measured in the lab. You will next be asked to participate in 3D body scanning, using a non-invasive 3D body scanner, located in a private room within the lab. Four scans will be conducted each while you are wearing different clothing ensembles: 1) only undergarments, 2) undergarments with a cotton t-shirt, station pants and body armor without hard plates inserted, 3) undergarments with a cotton t-shirt, station pants, and body armor with hard plates inserted, 4) undergarments with a cotton t-shirt, body armor with hard plates inserted and full police uniform including uniform shirt, pants, shoes, and duty belt. All scanning and clothing changes will take place in a private room. After the body scanning is complete, you will be asked to participate in a task analysis experiment while wearing your entire police uniform (provided by you), including body armor (provided by the researchers). During the task analysis, you will be asked to complete basic physical tasks such as walking, crawling, and moving from a standing to sitting position. All the tasks will be completed first while wearing the body armor without hard plates inserted and again with hard plates inserted in the body armor vest. Throughout the physical task analysis, you will be asked questions about the comfort of the body armor. Upon completion of the task analysis you will be asked to answer a few questions about your overall experience. With your permission, the task analysis and exit interview will be video and audio recorded. After the first visit, you will be asked to visit the lab one more time to repeat the 3D scanning and the task analysis procedures wearing a different body armor model.

**ARE THERE REASONS WHY I SHOULD NOT TAKE PART IN THIS STUDY?** You should not participate in this study if you do not meet the inclusion criteria or do not feel comfortable with the research procedures described above.

**WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?** The physical tasks in this study are designed to represent daily activities and should present no more than a minimal risk to you. It is not possible to identify all potential risks in research procedures, but the researchers have taken reasonable safeguards to minimize any known and potential, but unknown, risks.

**ARE THERE ANY BENEFITS FROM TAKING PART IN THIS STUDY?** While there is no direct benefit for taking part in this study, your study participation may contribute to increased knowledge of body armor. This knowledge will be used to improve the fit and comfort of the case company’s product, leading to improved occupational safety for those who wear body armor on the job.

**DO I HAVE TO TAKE PART IN THE STUDY?** Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.

**WHO WILL SEE THE INFORMATION THAT I GIVE?** We will keep private all research records that identify you, to the extent allowed by law. For this study, we will assign a code to your data (e.g., “Participant 1”) so that the only place your name will appear in our records is on the consent and in our data spreadsheet which links you to your code. If necessary, the Colorado State University Institutional Review Board (CSU IRB) and the study investigators may inspect these records. In addition, for funded studies, the CSU financial management team may also request an audit of research expenditures. For financial audits, only the fact that you participated would be shared, not any research data. All original data will be stored in the PI's research file storage and destroyed after three years of the study completion.

**CAN MY TAKING PART IN THE STUDY END EARLY?** If, for any reason, you wish to end your participation early, feel free to request the study investigator to make arrangements.

**WILL I RECEIVE ANY COMPENSATION FOR TAKING PART IN THIS STUDY?** Upon completion of your commitment to participate in this research you will be compensated through a product incentive. The case company will provide, at no cost to you, one [redacted] a Level IIIA concealable shield, which retails for about $100. (See details of the product [redacted] .You will also be reimbursed for the cost of traveling to and from the CSU laboratory. Round trip mileage will be reimbursed from your home address to the CSU laboratory at a rate of $0.535/mile. The cost for you to park on CSU's campus will also be reimbursed.

**WHAT HAPPENS IF I AM INJURED BECAUSE OF THE RESEARCH?** The Colorado Governmental Immunity Act determines and may limit Colorado State University's legal responsibility if an injury happens because of this study. Claims against the University must be filed within 180 days of the injury.

**WHAT ELSE DO I NEED TO KNOW?**

The researchers would like to video and audiotape your interviews to be sure that your comments are accurately recorded. Only our research team will have access to the files, and they will be destroyed when they have been transcribed

Do you give the researchers permission to video and audiotape your interviews?

☐ Yes,

☐ No

**WHAT IF I HAVE QUESTIONS?** Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions about the study, you can contact Brittany Conroy, at Britt.Conroy@colostate.edu or Dr. Juyeon Park, PhD at Juyeon.Park@colostate.edu. If you have any questions about your rights as a volunteer in this research, contact the CSU IRB at: RICRO_IRB@mail.colostate.edu; 970-491- 1553. We will give you a copy of this consent form to take with you

If you are interested in participating in this project, please sign below. Your signature acknowledges that you have read the information stated and willingly sign this consent form. Your signature also acknowledges that you have received, on the date signed, a copy of this document containing 3 pages.

____________________________________________

_______________________

Signature of person agreeing to take part in the study Date

__________________________________________
Printed name of person agreeing to take part in the study

________________________________________
______________________
Name of person providing information to participant Date

___________________________________
Signature of Research Staff
Do you consent to be audio and videotaped for this research? ____Yes _____No

# APPENDIX D: PHASE 1 CASE COMPANY INTERVIEW QUESTIONS

**Phase 1 Case Company Interview Questions**

These questions are designed to drive the line of inquiry and learn what the company is experiencing regarding their body armor products. The interviews will be conducted in a semi-structured manner, but these questions will be used to help generate conversation about the body armor, the return rate, the customer feedback the company has received, and the previous attempts to resolve the problems with fit and comfort.

1. How do you currently determine a customer's size in your body armor?
2. What measurements do you need from the customer's body?
3. How do you usually obtain those measurements?
4. How do you convert those body measurements to a garment size?
5. Are there any documents related to body armor sizing that I should review?
6. Do you know what the current return rate of the body armor vests is right now?
7. When vests are returned what kind of feedback do you get from the customers?
8. In what form is this feedback? Is it usually sent through the web, e-mail, phone, or some other way?
9. If the feedback is in a written format, may I view and analyze the customer comments?
10. Is there anything you hear from customers repeatedly?
11. Are there any other common complaints about the body armor fit and comfort?
12. How is the product review on the body armor vests affecting the company as a whole? How has it affected your responsibilities?
13. Are there any documents tracking the return rate? May I view them with you?
14. What are you most concerned about in regard to the fit and comfort of the body armor?
15. Have you made any changes to the body armor design to address these problems?
16. If so, what kind of changes?
17. Do you know of any results of those changes?
18. Is there any documentation of these changes or the results that I may see/read?
19. Has anything else been done at the company to address the body armor return rate?
20. Do you wear the body armor yourself?
21. If so, do you find it comfortable?
22. If you could change anything about the body armor what would it be?
23. Are there any other documents that will help me understand what the company has been experiencing with the fit and comfort of the body armor product and/or the returns?

# APPENDIX E: HBD QUESTIONNAIRE

## Human Body Dimensioning Questionnaire: Lab 141 Gifford

Questionnaire for 3-dimensional Body Scanning – [TC]2, model KX-16
Please take a few minutes to fill out this survey for new participants, prior to 3D scanning.

**Background Information:**

***Sex:*** ☐ *Male* ☐ *Female*

***Age:*** ________________________________ *years old.*

***Physical Profile:***

Shirt size (circle): XS S M L XL 2XL 3XL 4XL

***Marital Status:***

☐ Single ☐ Married ☐ Divorced
☐ Widowed ☐ Other__________________________________.

***Education:***

☐ High school diploma ☐ Some college or currently in school ☐ Bachelor's degree
☐ Professional degree ☐ Graduate degree

***Employment Status: (check all that apply)***

☐ Employed ☐ Unemployed ☐ Student

***Ethnicity: (check all that apply)***

☐ Native American ☐ African American ☐ Caucasian
☐ Asian ☐ Hispanic/Latino ☐ Pacific Islander
☐ Multiracial ☐ Prefer not to say

***Occupation and Body Armor:***

Are you now or have you previously been employed as a law enforcement officer?
☐ YES ☐ NO ☐ Other___________.

If so, what is your rank/title as a law enforcement officer?: ___________ year(s) ___________ month(s)

Are you required to wear your body armor on the job?
☐ YES ☐ NO ☐ Other___________.

For the past six months, on average how many times a month did you wear your body armor for work?_____________________________________________________________.
For the past six months, on average how many hours per month did you wear your body armor for work?__________________________________________________________.

# APPENDIX F: TASK ANAYLSIS INSTRUMENT

## Introduction

The tasks for this test have been adopted from an ASTM standard for comfort of protective equipment. I’ve added scenarios of how these relate your on-the-job activities. If you have any suggestions on how I can improve the scenarios, please let me know.

**Occupational Task Analysis Instrument: Body Armor**

Directions: The researcher is to read the task directions out loud to the participant and demonstrate the movement if necessary. After the task has been completed by the participant, the researcher will ask the questions aloud and mark the participant's responses accordingly. Audio recording will take place from start to finish to capture any comments the participants make before, during and after the tasks.

As we begin, remember to keep comfort in mind as you answer the questions about the tasks. If at any time you do not wish to complete a task, or need to stop, please let me know. If you don't wish to answer a question, or don't have an opinion, that's fine to say as well.

**Task One**: I understand you may need to kneel while on duty. Please kneel on your left knee, then move so you are kneeling on both knees, kneel on the right knee and move to a standing position. Repeat this movement four times.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**<u>Task Two</u>**: I understanding ducking or squatting is something that you might need to do on duty? Please perform task two by performing the following action: Duck, squat, pivot right, pivot left, stand. Repeat movement four times.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**Task Three**: Stand erect. Extend arms over head, then bend elbows. Repeat movement four times. This motion may be similar to that performed if you needed to pull yourself onto or over something, or jump a fence while on duty.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**Task Four**: Please stand erect, without using a firearm, please demonstrate the motion that you would take to reach for your firearm, remove it from the holster and draw it while on duty. Demonstrate the motions you would use to return it to the holster. Repeat 4 times.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**<u>Task Five</u>**: Imagine you need to reach for your radio on the opposite shoulder. Stand erect. Reach arms across chest completely to opposite sides (left then right) and repeat movement four times.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**<u>Task Six:</u>** Walk a distance of 100 yards.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**<u>Task Seven</u>**: Crawl on hands and knees a distance of 20 feet.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**Task Eight**: Stand erect. Turn head to the left and return to a neutral position. Turn head to right and return to a neutral position. Then look up at the ceiling, and down to the floor. Repeat the movement four times.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**<u>Task Nine</u>**: This task is representative of sitting down at a desk. Stand erect beside chair. Sit in chair. Return to a standing position beside the chair. Repeat four times.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**Task Ten**: I understand you may need to pick things off the ground, or move evidence boxes while on duty. Individually lift four boxes from the floor and place on a table. Return each box to the floor, one at a time.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**<u>Task Eleven</u>**: Step up five stairs, turn around and step down.

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

**<u>Task Twelve</u>**: I understand you may need to climb a ladder like the ladder on the outside of the building while on duty. Please climb to the fifth rung of a ladder. You do not need to stand up straight at the top, due to the low ceiling it would be better if you stayed bent on the top rung. Please be careful that you don't hit your head on the ceiling!

***Please rate your level of comfort using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor while performing task 1:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor during the task?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

# Comfort Overall

***Please consider your overall comfort for the last twelve activities. Please rate your level of comfort overall using the following scales: 1 being extremely uncomfortable and 7 being extremely comfortable***

---

Overall comfort of the body armor:

1 2 3 4 5 6 7

Comfort of the body armor around the neck

1 2 3 4 5 6 7

Comfort of the body armor around the chest

1 2 3 4 5 6 7

Comfort of the body armor around the waist

1 2 3 4 5 6 7

Comfort of the body armor around the arms.

1 2 3 4 5 6 7

Can you share more details on the comfort of the body armor?

Are there any areas of the vest that bothered you?

Did the vest prevent you from moving as you normally would? Y/N

***Please consider your overall experience with this body armor. Please mark with an "X" how you would describe your vest when considering your overall perception of the garment using the following descriptors:***

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Comfortable** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Uncomfortable** |
| **Acceptable** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Unacceptable** |
| **Rigid** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Flexible** |
| **Easy to move in** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Hard to move in** |
| **Cold** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Hot** |
| **Bulky** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Not Bulky** |
| **Soft on skin** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Rough on Skin** |
| **Nonabsorbent** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Absorbent** |
| **Hard to take off** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Easy to take off** |
| **Unsafe** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Safe** |
| **Breathable** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Does not breath** |
| **Feels supple** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Feels stiff** |
| **Lightweight** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Heavyweight** |
| **Not sturdy** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Sturdy** |
| **Easy to put on** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Hard to put on** |
| **High quality** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Low quality** |
| **Irritating** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Non-irritating** |
| **Nonfunctional** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Functional** |
| **Fits well** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Does not fit well** |
| **Like** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Dislike** |
| **Lack of protection** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Provides protection** |
| **Loose** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Tight** |
| **Overall satisfied** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **Overall dissatisfied** |

# APPENDIX G:  USER EXIT INTERVIEW QUESTIONS

**Participant exit interview questions**

1. Is there anything else you want to share about your experience wearing body armor in the past or today?
2. You have indicated that are or are not required to wear your body armor on the job:
3. If you are required to wear body armor on the time. Are you required to wear it all the time or under certain conditions?
4. If you are not required to wear body amour on the job, do you wear it on the job voluntarily?
5. If so, under what conditions do you volunteer to wear it?
6. (After wearing the prototyped body armor) Given the choice, do you think you would wear this body armor instead of your current body armor model? Why or why not?
7. If  body armor was more comfortable would you be more likely to wear it (given the choice)? Why or why not?
8. What could make the body armor more comfortable to you?

# APPENDIX H:  CASE COMPANY FOCUS GROUP QUESTIONS (STAGE 3)

**Case Company Focus Group Questions**

1. What do you like about the prototype overall?
2. What do you not like about the prototype overall?
3. What do you think about the changes in the width of the chest?
4. What do you think about the changes in the width of the waist?
5. What do you think about the changes in the shape that the chest and waist changes create (A-shaped versus barrel shaped)?
6. Do you see a benefit to these changes?
7. Do you see any challenges or risks to these changes?
8. Do you think it would be helpful to incorporate these design changes into your regular model of the body armor product?
9. If so, which ones, and why?
10. How can we plan to implement these changes?
11. Which changes will be implemented and over what time frame?
12. Previously, you've shared quite a bit about your current sizing system with me.
13. Do you see this garment fitting into your current sizing system? Why or why not?
14. Do you see this garment changing your current sizing system? If so, how?
15. What benefits might this afford?
16. What challenges does it present?
17. As I explained to you, I used a combination of 3D body scanning, a task based analysis with subjective comfort ratings, and interviews to assess the fit and comfort of the product. Can you relate these methodologies to your company's practice?

18. Do you see a benefit to incorporating any of these into your current practices? If so, which ones and why?
19. Do you see any challenges to incorporating these? If so, which ones and why?
20. What do you see as the main take-aways from this collaboration? Overall how do you think it has benefited you?
21. Is there anything else you would like to talk about to wrap up your perspectives on this collaboration and the resulting prototype?