Development of Firefighters' Helmet and Self-Contained Breathing Apparatus (SCBA) Harness for Improving Upper Body Movement

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by

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ABSTRACT

Wearing correctly fitting fire gear is essential for firefighters' safety, work performance, and wearing satisfaction in the field. However, a self-contained breathing apparatus (SCBA) and fire helmet have no size options with specific descriptions. In addition, a male-centered design practice increases these restrictions when female firefighters use the gear. This study aims to provide an optimal fit of SCBA harnesses and fire helmets for firefighters by applying additional fit-adjustable design features. This study identified the design and fit issues that female and male firefighters experience. Based on the study participants' empirical feedback, fit-adjustable SCBA harness and fire helmet prototypes were developed and then evaluated by 3D body scanning and surveys. The findings indicated an improvement in the range of motion of firefighters' upper body and wearing stability when wearing the prototypes compared with conventional SCBA harness and fire helmet designs. Through this study, a possibility for fit optimization design was suggested based on the consideration of firefighters' anthropometric data by gender.

BIOGRAPHICAL SKETCH

Yoojin Chung was born in Seoul, South Korea in January 1992. In 2011, she entered the Fine Arts College of Hong-Ik University in Seoul. During her earning a bachelor's degree in textile art and fashion design, she was eager to solve social problems through creative garment designs. Her passion for contribution to the humane society has led her to develop such skills as garment-making, weaving, knitting, felting, and tapestrying as well as incorporating unusual materials into fashion artworks. The creative work experiences at the art college led her to desire practical design projects to affect individuals and society by creating functional clothing. Yoojin started her research career in the Intelligent & Interactive Robotics Center at the Korea Institute of Science and Technology (KIST) as a student intern and wearable device designer from July 2015. Her research focused on the development of the textile electrode system and optimal wearable device design for bionic signal acquisition and continued her career at the robotics center for 16 months. Yoojin graduated from Hong-Ik University in February 2017 with a Bachelor of Fine Arts degree in Textile Art and Fashion Design and, in August 2017, she entered graduate school at Cornell University (Apparel Design). As a graduate student, she served as a research assistant at the Performance Apparel Design Lab. During her master’s study, two of her design entries were exhibited at the annual conference of the International Textile and Apparel Association (ITAA) and a team project paper was presented at the annual conference of Human Factors and Ergonomic Society (HFES). Yoojin will continue her studies in functional apparel, especially, development of E-textile and Exo-suit in Bionics Center at KIST, Seoul, as a researcher and wearable device designer.

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TABLE OF CONTENTS

Title Page……………………………………………………………..…………….……i

Abstract …………………………...……………………………......……...…...…iii

Biographical Sketch ………………………………………..…………...…iv

Acknowledgements ……………...…………………………...…….……………….v

Table of Contents …….……………………………………...…...………...…vi

List of Figures ………..…………………….…...….………………………...ix

List of Tables………. ………………………………...……………………... xi

List of Abbreviations ……………………………………………………….. xii

Chapter 1: Background …………..………...………………………………………1

1.1 The Necessity of Wearing Firefighters' PPE …….…………………1

1.2 Adverse Effects of Firefighters' PPE …….…………………………….2

1.3 The Need to Improve the Fit of SCBA Harness and Helmets ……...4

Chapter 2: Literature Review…………….…...………………………………….………6

2.1 Impact of Self-Contained Breathing Apparatus (SCBA) …….……...8

2.2 Fire Helmet Design Issues ………...………………………………14

Chapter 3: Methods………..…..……………………………………...………...... 18

3.1 Phase Ⅰ: Design Development of Compatible Firefighters' PPE ….18

3.1.1 Development of Prototype 1 ……………………………..….20

3.1.1.1 Development of SCBA Harness Prototype 1 …..20

3.1.1.2 Development of Fire Helmet Prototype 1 ……..22

3.1.2 Empirical Data Collection of Firefighters' PPE Design …..…..……..…..……..…..…..…..….…..….…..…......24

3.1.2.1 Data Collection for Empirical Feedback of Conventional PPE Design …………......…...….....…....…...25

3.1.2.2 Data Collection for Empirical Suggestion of Improving PPE Design ………………..……..………..25

3.1.2.3 Data Collection for Empirical Review of Prototype 1 ………………………………….. …………………...27

3.2 Phase Ⅱ: Design Development and Evaluation of Compatible Firefighters' PPE ……………………………………….……………29

3.2.1 Development of Prototype 2 ……………………………29

3.2.1.1 Development of SCBA Harness Prototype 2 ….30

3.2.1.2 Development of Fire Helmet prototype 2 ……...32

3.2.2 Design Evaluation Method of Prototype 2 ………………33

Chapter 4: Results and Discussion ..…………………………………………….....37

4.1 Phase Ⅰ: Design Development of Firefighters' PPE for Improved Compatibility ……………………………………..………..……39

4.1.1 Empirical Review of Conventional Firefighters' PPE Design……………………………………………………………..39

4.1.1.1 Review of SCBA Design ……………………...39

4.1.1.2 Review of Fire Helmet Design ………………..51

4.1.2 Empirical Suggestion for Improving Firefighters' PPE Design ………………………………………..………… 58

4.1.2.1 Suggestion for SCBA Design …………………58

4.1.2.2 Suggestion for Fire Helmet Design ……………64

4.1.3 Empirical Review of Prototype 1 ………………………..67

4.1.3.1 SCBA Harness Prototype 1 Review …………...67

4.1.3.2 Fire Helmet Prototype 1 Review ………………69

4.1.4 Summary of Empirical Reviews for PPE Design Development …….…………………….……………….…….……..70

4.2 Phase Ⅱ: Design Evaluation of Compatible Firefighters' PPE …………………………………………………….………..……….…72

4.2.1 Design Evaluation of SCBA Harness Prototype 2 ..……..73

4.2.2 Design Evaluation of Fire Helmet Prototype 2 …………..78

4.2.3 Summary of Design Validity of Prototype 2 ……...……...81

Chapter 5: Conclusion ……….…..…………………………………………….83

References ……….…..…………………………………………..……….87

Appendix 1: Approval Letters of Institution Review Board for This Study ……….96

LIST OF FIGURES

Figure 1: Personal protective equipment (PPE) for firefighters ……………..…… 2

Figure 2: Harness (carrying system) components of an SCBA ……………...…… 9

Figure 3: Different distances between the air tank and helmet, by torso length and height …………..……….……….…………….……….…………….……..12

Figure 4: Components of a structural fire helmet …………….…………….……....15

Figure 5: Prototype development and evaluation process …..…………………… 19

Figure 6: The main design concepts of SCBA harness prototype 1 ……………… 20

Figure 7: (a) Fixed position of a conventional SCBA; (b) height-adjustable waist belt of prototype 1 …….……………….…….………………….…….…………….…….…… 22

Figure 8: The main design concepts of fire helmet prototype 1 ………………… 23

Figure 9: The conventional helmet (left) and helmet prototype 1 (right) ……….. 24

Figure 10: Sliding device of the height-adjustable waist belt ....……………….. 31

Figure 11: The height-adjustable range of prototype 2 (a) and other design details (b) …….……….……….……….……….……….……….……….……….……….…… 31

Figure 12: The second helmet prototype ……………………….……..…………. 33

Figure 13: Placement of retroreflective markers ……………….……....….…….. 36

Figure 14: Upper body postures for evaluating SCBA designs ……………….... 37

Figure 15: Neck movement postures for evaluating helmet designs ……………. 38

Figure 16: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional SCBA sizing system ………………………………… 45

Figure 17: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional SCBA design and fit ………………………………… 45

Figure 18: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional SCBA fit and need for additional fit adjustment ……. 48

Figure 19: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional SCBA wearing comfort ………………………….…. 49

Figure 20: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional fire helmet sizing system ……………...……………. 55
Figure 21: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional fire helmet design and fit ……………...…………… 55
Figure 22: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional fire helmet fit and need for additional fit adjustment …56
Figure 23: The means and standard deviations of the U.S. firefighters' ratings of evaluation of conventional fire helmet wearing comfort ……………...………… 56
Figure 24: Key design points of SCBA prototype 1 ……………...……………… 68
Figure 25: Fire helmet prototype 1 with the extended liner ……………...……… 70
Figure 26: Key design points of SCBA harness prototype 2 and height-adjustable range of waist belt ……………...…………………………………….….….…… 72
Figure 27: Key design points of fire helmet prototype 2 and adopted Boa dial for fit adjustment of the extended liner ……………...…………………………….……... 78

LIST OF TABLES

Table 1: Summary statistics for measured dimensions ..…………………………….…….…… 7

Table 2: Demographic details for research participants in phase 1 ……………….....…… 19

Table 3: Online survey questions of conventional PPE design ………………………….... 26

Table 4: Interview outline and discussion topics for PPE design improvement …….……. 28

Table 5: Independent variables and testing groups …...…………………………...…… 33

Table 6: Questions for design evaluation of prototype 2 designs ……………………….... 36

Table 7: Means and standard deviation of ratings of evaluations of conventional SCBA design ……………………...…………………………………………..…..….…... 40

Table 8: Means and standard deviation of ratings of evaluations of conventional Turnout Ensemble Pocket Design ……..…………………………………………………….…… 43

Table 9: Means and standard deviation of the U.S. firefighters' ratings of evaluations of the conventional SCBA chest strap ………………………………………………………… 46

Table 10: Pearson correlation analysis between the U.S. firefighters' height and satisfaction in conventional SCBA design ……………………..…………………………………… 50

Table 11: Means and standard deviation of ratings of evaluations of conventional fire helmet design ……………………...…………………………………………..…..….….. 52

Table 12: Pearson correlation analysis between U.S. firefighters' height and satisfaction in conventional fire helmet design ……………………...……………………………….. 57

Table 13: Shapiro-Wilk normality test for verifying static ROM data analysis …….…… 73

Table 14: Wilcoxon signed ranks test comparison regarding satisfaction in the use of SCBA by type of gear (conventional SCBA and prototype 2) …………………..……………….. 75

Table 15: Dependent T-test and Wilcoxon signed ranks test comparison regarding static ROM with SCBA and fire helmet ……………...…………………………...…….……. 77

Table 16: Wilcoxon signed ranks test comparison regarding satisfaction in the use of fire helmet by type of gear (conventional fire helmet and prototype 2) ………………….…… 79

Table 17: Dependent T-test regarding the degree of movement matching of fire helmet and neck movement ……………...………………………………...………………...……. 81

LIST OF ABBREVIATIONS

3D	Three-Dimension
BMI	Body Mass Index
Max	Maximum
Min	Minimum
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
PPE	Personal Protective Equipment
ROM	Range of Motion
SCBA	Self-Contained Breathing Apparatus

CHAPTER 1

Background

Firefighting is one of the most respected occupations in the world, as it requires both courage and sacrifice to serve one's community. Firefighters are often engaged in physically demanding activities in hazardous environments (Coca et al., 2008), and their work in these unfavorable conditions increases the risk of injuries and fatalities. As a result, the rate of injuries incurred in firefighting situations is significantly higher than in other occupations (Guidotti & Clough, 1992).

According to the U.S. Department of Labor (2006), fatal injuries occurred 4.15 times more often among firefighters than those employed in other types of workplaces. In 2016, 39.2% (N=24,325) of all firefighter injuries occurred on the ground; this was the lowest rate since 1981 (Haynes & Molis, 2017). About 50% of firefighters' injuries are closely related to the musculoskeletal system, such as overexertion, strains, falls, jumps, slips, and tripping. Other common types of injuries, such as those to the skin (wounds, cuts, bleeding, and bruises), smoke inhalation, and thermal stress, only account for 15%, 7%, and 5% of cases, respectively (Evarts & Molis, 2018). In particular, wet and slippery conditions and limited visibility can induce physical injuries such as slips, trips, and falling (Rosengren et al., 2014).

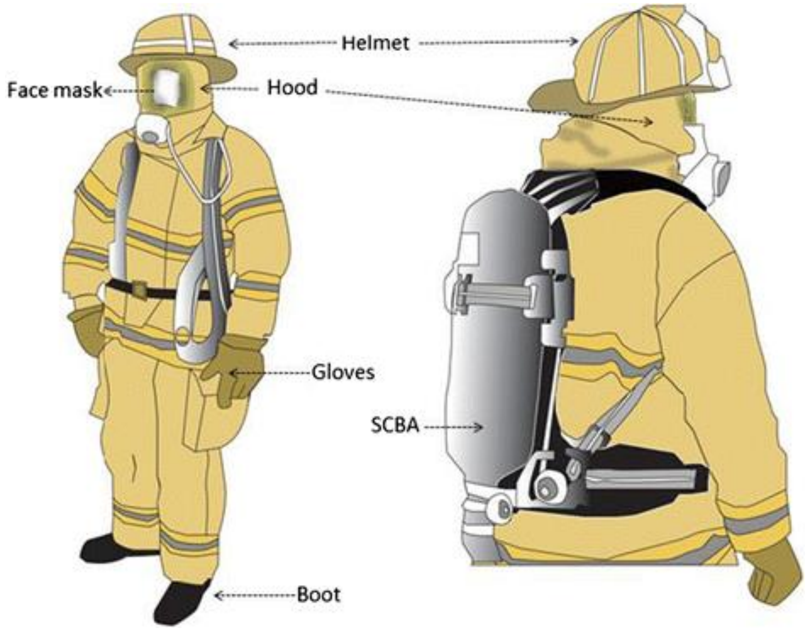
1.1 The Necessity of Wearing Firefighters' PPE

Personal protective equipment (PPE) for firefighters includes a turnout coat, pants, self-contained breathing apparatus (SCBA), boots, hood, helmet, and gloves

(Figure 1). Wearing firefighting PPE is mandatory so that every firefighter can perform their duties while maximizing safety (Boorady et al., 2013a). PPE is mainly designed for thermal protection, and the latest developments in firefighting PPE have contributed to a decrease in firefighters' burn injuries, heat stress, and moisture build-up (Boorady et al., 2013a; Francescani, 2001).

Figure 1

Personal Protective Equipment (PPE) for firefighters



Note. This figure of the configuration of firefighter's PPE was adapted from "Assessment of Firefighters' Needs for Personal Protective Equipment", by H. Park et al., 2014, *Fashion and Textiles, 1*(1), p. 9. Copyright 2014 by the Springer Open.

1.2 Adverse Effects of Wearing Firefighters' PPE

While fighting a fire, PPE can provide thermal protection, but the added weight and bulk of PPE can induce mobility restrictions, physical strains, and discomfort among firefighters by adding a considerable physical burden (Adams & Keyserling, 1996; Boorady et al., 2013a; Chiou et al., 2012; Coca et al., 2008; Huck, 1991; Huck & McCullough, 1988; Park et al., 2014; Smith, 2008). Furthermore, PPE can work negatively against firefighters, as they must carry additional weight into the fireground while they are exposed to a completely dark and obstacle-filled environment (Rossi, 2003). These conditions can have a negative impact on firefighters' work performance and safety.

Boorady (2011) notes that it is desirable for wearers to be able to move without strain or restrictions while using a protective clothing system, and that the quality of wearers' mobility and movement is closely related to the system's fit. This is because the accommodation between the body's movement and the clothing is critical for the optimal performance of the clothing system. A good fit for functional clothing should not restrict body movement or hinder the performance of required tasks (Boorady, 2011). Previous studies have shown that, while firefighters' PPE protects them from external risks, wearing the equipment can have adverse effects on their range of motion (ROM), mobility, and comfort. Such problems can be made worse if the gear does not fit the firefighter's body well (Havenith & Heus, 2004; Huck 1988, 1991). Generally speaking, firefighters' PPE weighs between 75 and 100 pounds (Boorady et al., 2013a). The heavyweight and bulkiness of the PPE can produce adverse effects and hinder firefighters' job performance (Chiou et al., 2012; Punakallio, 2005; Sobeih et al., 2006). To reduce firefighters' injuries and body movement restrictions, some researchers have put an emphasis on the need for an ergonomic approach to PPE design, with all components based on an understanding of human factors (Boorady et al., 2013a; Park et al., 2014). The fit of firefighting gear is one of the influential factors affecting performance and injuries on the fireground (Rosengren et al., 2014). Thus, ensuring a proper fit is critical for minimizing PPEs' adverse effects on firefighters.

According to Routley (2006) and Hsiao et al. (2014), understanding firefighters' anthropometric data is significant for improving the design of fire gear, and for ensuring a proper design approach to protecting firefighters from injuries. However, firefighters' body shapes, the main determinant of garment fit, are unique by gender and individual, and the customization of fire garments and equipment is not realistic for manufacturers. Boorady (2011) notes, however, that size-adjustable design features are necessary for all functional clothing items because the increased options afforded by size adjustment capabilities mean a proper fit is possible. The clothing should be able to work properly for an unknown population of varying body shapes and sizes.

1.3 The Need to Improve the Fit of SCBA Harness and Helmets

Among all PPE items, SCBA and helmets have the most rigid surfaces, apart from other equipment with no sizing options. The inflexibility of the worn materials is usually considered an important factor that restricts the wearer's mobility and decreases their sensorial comfort by creating a poor fit or restricted body movements (Kayseri et al., 2012; Kuklane & Holmér, 2000; Park et al., 2014; Park et al., 2015). The Occupational Safety and Health Administration (2003) requires that fit and comfort be considered when choosing PPE. The National Fire Protection Association's (NFPA) 1971 standards on protective ensembles for structure firefighting and proximity firefighting (2018) also mention that providing multiple sizes by following sizing increment guidelines when PPE is manufactured is required. According to NFPA 1971 standards, no design requirements are specified regarding sizing options or increments for an SCBA harness system and fire helmet, though the sizing systems for the garment, glove, and footwear are specified. Furthermore, Park et al. (2019) pointed out that the SCBA body part has no size options apart from the size option for the air capacity of the air cylinder, although firefighters have a wide range of torso lengths. Especially, female firefighters often express complaints about the poor fit and discomfort of wearing SCBA due to the less size consideration of the females' body (Lee et al., 2015).

Considering that every individual is physically unique, it is impossible for the size chart of one brand to accommodate the body features of all individuals, even if the chart has been developed based on a large set of anthropometric data. In addition, due to the unique shapes and features of each firefighter's body, some may have specific preferences for positioning clothing components, which can make their use easier and more accessible. This raises the need for an improvement in the optimization of fit and accommodation for each firefighter's preferences in the perceived fit and comfort of their SCBA harness system and helmet.

With the above in mind, this study explores how to enhance firefighters' performance quality and satisfaction when they wear PPE that has been optimized for fit and comfort, especially in the SCBA harness and helmet. The purpose of this study is to develop a new SCBA harness design and helmet liner to improve fit and mobility for firefighters who have different body dimensions and fit preferences. Therefore, this study focuses primarily on fit optimization by developing fit-adjustable design features and strives to answer the following two research questions below.

- Q1: How can firefighters' upper body movement be enhanced through additional size-adjustable design features?
- Q2: How can firefighters' satisfaction of wearing PPE be enhanced with a fit-optimized SCBA harness and helmet?

CHAPTER 2

Literature Review

To identify design issues related to conventional SCBA harnesses and fire helmets, this study must first identify the anthropometric differences among firefighters in terms of their individual and gender-related characteristics, because these affect the quality of fit and wearing satisfaction. Park et al. (2019) found that the larger the proportion of the body fire gear covers, the greater the physical burden imposed on the wearer, due to its heavy weight and bulkiness. Consequently, smaller firefighters tend to be more vulnerable to injuries on the fireground, when compared to their larger colleagues. In addition, the added weight from the fire gear and the workload from their duties increase levels of heat stress and decrease their work performance (Boorady et al., 2013a). In general, female firefighters have smaller body sizes than males. According to a national report (U.S.) on women in firefighting (Hulett et al., 2008), 79.7% of female firefighters complained about the ill-fitting nature of firefighting personal protective equipment (PPE), whereas only 20.9% of male firefighters did so. Female firefighters report feeling unsatisfied with the fit of fire gear because firefighters' PPE has been designed from a male-centered design approach. This means that female firefighters generally wear bulkier gear designed for men (Boorady et al., 2013b; Park & Hahn, 2014).

Although many female firefighters try to devise their own biomechanical techniques for the easier use of heavy and bulky fire gear originally designed for males (Park, Trejo et al., 2015), it is true that female firefighters are more vulnerable to injuries than male firefighters, due to the ill-fit of their gear (Hulett et al., 2008;

Park & Hahn, 2014; Sinden et al., 2013). The average adult female's body size is 93% of the average adult male's body size; in other words, the 50th percentile for female adults is equivalent to the 5th percentile among males. The solution here is not simply to order smaller male fire gear for female firefighters, because they also have different body dimensions and proportions (Hulett et al., 2008). A previous study stated that, for the development of protective equipment design, the specific anthropometric approach should be required (Hsiao, 2013). A firefighter body measurement study, for instance, noted that the torso dimension data should be considered when designing the SCBA sizing system and design (Hsiao et al., 2014). The study collected U.S. firefighters' body dimension data and reported the mean difference of firefighters' torso and head dimension data, which would be considered for the harness and helmet design, by type of gender (Table 1). Further study for a

Table 1

Summary Statistics for Measured Dimensions (unit: mm)

Posture	Body Dimension	Weighted Mean	
		Male	Female
Standing	Hip Circumference	1077	1058
	Vertical Trunk Circumference	1775	1607
	Waist Circumference	1032	994
Sitting	Acromion Breath	387	355
	Hip Breath	437	425

Note. This table was reproduced based on the data from "Sizing Firefighters: Method and Implications", by H. Hsiao et al., 2014, *Human Factors*, *56*(5), pp. 881–882. Copyright 2014 by Sage Journals.

specific design approach considering the gender difference in body dimension is also required for the development of a good fit of fire gear.

These differences in the body dimensions of males and females are considerable human factor issues when developing PPE designs (Park et al., 2014). Park and Hahn (2014) reported that female firefighters have lower satisfaction with the fit of PPE, which is related to the use of the equipment, than male firefighters. Furthermore, in that study, female firefighters pointed out that careful consideration of the anthropometric data of job-related active postures is required to improve the fit and sizing systems of PPE. Understanding human factors in job-related tasks is an important design consideration when designing fire gear (Park et al., 2014). The wearability and proper use of firefighting PPE can be improved when human factors are considered in the gear development process, alongside the input of empirical data (Akbar-Khanzadeh et al., 1995; Huck, 1988). Park et al. (2014) reported that considering human factors is the major concern of firefighters when working to enhance firefighters' satisfaction with their gear in terms of mobility, safety, and comfort. The human factors include the size and fit of fire gear and the protection quality of each piece of gear's connecting parts. Compatibility among the pieces of gear is another main design concern for their proper function and according to their desired purpose (Park & Hahn, 2014).

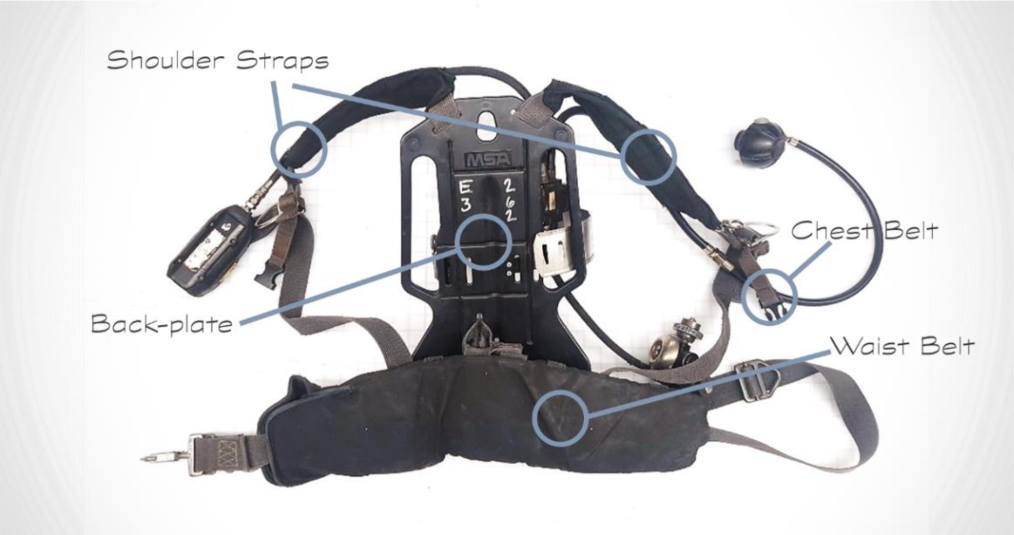
2. 1 Impact of Self-Contained Breathing Apparatus (SCBA)

The SCBA is the single most influential piece of firefighting gear when it comes to negative effects on body balance (Park et al., 2010; Park et al., 2014; Punakallio, 2005), and wearing the apparatus increases the consumption of oxygen and the body's metabolic rate (Bakri et al., 2012). The physical burden of wearing an SCBA can also increase falls and slipping injuries (Helneman et al., 1989; Park et al., 2010). The burden also disrupts gait patterns through the center of gravity change upward and backward out of the pelvis, compared to the unloaded status of an SCBA (Park et al. 2010; Park et al. 2014). An SCBA consists of a high-pressure air tank, a pressure regulator, and an inhalation connection. These are connected and mounted to a harness (carrying frame); among these, the heaviest component is the air tank (International Fire Service Training Association, 2008). The SCBA harness includes a back plate, shoulder straps, waist belt, and chest strap, as shown in Figure 2 (Bakri et al., 2012).

Rosengren et al. (2014) noted that, with an increase in weight and the bulkiness of the SCBA's air tank, the instability of medial-lateral postural sway increases and gait performance decreases. This is because the step length gets shorter with the larger volume of the apparatus, thus increasing the risk of firefighters hitting obstacles on the fireground. This adverse impact of wearing SCBA can be greater among smaller firefighters (Marshall, 1980; Park et al., 2014).

Figure 2

Harness (Carrying System) Components of an SCBA



This is because the weight and bulkiness of the SCBA create a bigger shift in the center of gravity, accounting for a larger proportion of shorter firefighters' body dimensions, compared to taller firefighters. While the SCBA induces injuries through falls or slips, the apparatus is also closely related to musculoskeletal pains from its improper placement and the restriction of bodily movements. Firefighters frequently experience the discomfort of wearing an SCBA and report the restricted movement of their arms, shoulder, back, and neck; muscle soreness in the shoulder or back pain are common chronic symptoms of carrying an SCBA (Park et al., 2014).

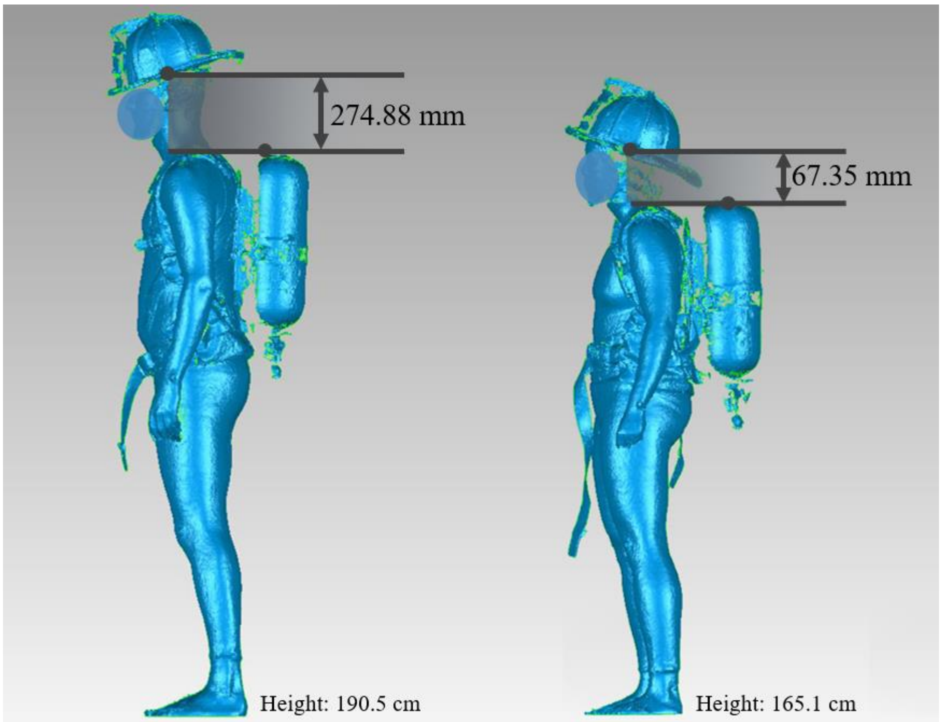
To relieve these problems, designs for a balanced weight distribution of the air tank around the body's trunk should be taken into account (Park et al., 2014). Lowering the air tank on the back can be an effective way to redistribute weight efficiently and would enhance firefighters' mobility and work performance (Griefahn et al., 2003; Park et al., 2014). It can also reduce shifts in the center of gravity (Park et al., 2014). A previous study by Holewijn and Lotent (1992) regarding backpack design found that placing a backpack's load near the waist and pelvis can decrease the wearer's discomfort and enhance mobility, compared to carrying loads on the shoulders, because it can minimize the loss of physical performance. According to Jones and Hooper (2005), even though the pelvis is a major load-bearing structure of the body and creates an appropriate region for supporting an external load, the incompatibility issue between the shoulder straps and waist belt of the SCBA harness can lead to much of the load being carried on the shoulders, rather than the pelvis. The fixed height of the waist belt can impede its placement at an optimal location where each person feels comfortable and effective in carrying the weight of the SCBA. With this in mind, designs that provide an appropriate air tank placement and harness fit should be developed for efficiently carrying the SCBA and enhancing firefighters' mobility and satisfaction with fit and wear.

The SCBA also leads to a change in the range of firefighters' neck movements. Firefighters complain about the physical conflict brought on by the long back brim of the fire helmet, which often hits the top of the SCBA's air tank. In fact, the torso length of firefighters affects both their neck movement and visibility, and the length of the firefighter's back determines where the air pack will be located on it (Park et al., 2014). Those firefighters whose torso length is relatively shorter may not have enough space for proper neck extension between the brim of their fire helmet and the top of the SCBA air tank, and the wider brim of the helmet may limit his or her range of sight (Figure 3). The conflict between the long back brim, originally designed to deflect water and debris, and the air tank causes the limitations in neck movements (Park & Hahn, 2015). Figure 3 indicates an example of the effects of the difference in distance between the two fire gears by the firefighter's height; in the figure, the perpendicular distance from the top spot of the air tank to the side center of the helmet was measured.

Besides, the height adjustment of the harness based only on the shoulder straps, the current fit-adjusting system of SCBA harness, can accelerate this problem among shorter firefighters. For example, if a firefighter with a short torso tries to tighten the shoulder straps to place his/her waist belt at an appropriate height (on the pelvis or waist), the air tank goes up. Then, the room for neck extension can be limited due to the high placement of the SCBA's air tank. However, the length of the back plate and air tank are fixed in general, even if the length differs slightly by the manufacturer. This incompatibility between the shoulder straps and waist belt results in a decreased range of motion (ROM) in the neck and a limited range of vision (Hulett et al., 2008; Park et al., 2014). According to Park et al. (2019), an SCBA air tank (which ranges in height between 46.2cm and 56.9 cm) covered

Figure 3

Different Distances between the Air Tank and Helmet, by Torso Length and Height



between 98% and 132% of the upper torso of their study's participants (16 males and 5 females, respectively). This means that a firefighter with a shorter torso length will have more limitations, not only in upper body movement, due to the stiffness and weight of the metal back plate and air tank, but also in neck movements, while increasing the possibility of the helmet's brim hitting the air cylinder.

Another mobility restriction associated with wearing an SCBA is observed in upper limb ROM. According to Son et al. (2010), wearing a 10-kilogram SCBA decreased whole body ROM by 13.7%, and upper body movement by 11.1%, due to its weight and shoulder straps. Their study stated that the pressure from the SCBA's weight and straps impedes the shoulder movement and results in upper body fatigue. Other studies have also noted shoulder and arm mobility reduction due to the SCBA (Park et al., 2014). Specifically, firefighters reported that wearing an SCBA restricts their arm movements, due to its weight and straps, by preventing them from reaching upward (Park et al., 2014). In addition, wearing an SCBA can negatively affect comfort during waist-bending movements (Son et al., 2010). Assuming a waist-bending posture can become difficult due to the wide width and stiffness of the SCBA waist belt (Lee et al., 2015). Furthermore, shifting the center of mass backward requires a wider ROM to move the body forward with the additional weight from the SCBA (Park et al., 2015). The added bulkiness and weight appear to cause chronic lumbar pain (Park et al., 2013).

The other incompatibility issue in SCBA harness design stems from the relationship between the SCBA harness and the turnout coat. The SCBA harness is always placed over the turnout coat of firefighters on the ground. However, the SCBA's chest strap and waist belt tend to block access to the turnout coat's pockets. There is empirical evidence that opening the pocket is difficult, due to these straps (Lee et al., 2015). In response, firefighters have requested that pockets be placed in convenient locations, to give them easy access to their contents (Boorady et al., 2013a; Park et al., 2014).

Each person has a unique body size and shape, and firefighters who have small and short body dimensions are more likely to be placed in vulnerable conditions while firefighting. In general, female firefighters have relatively smaller body mass and less muscle strength than males (Park & Hahn, 2014). According to the body measurement data of U.S. firefighters (Hsiao et al., 2014) by the National Institute for Occupational Safety and Health (NIOSH), the mean male torso length, that is, the vertical distance between the acromion and sitting surface in the sitting posture is 3.08 cm longer than the mean for females; this accounts for the 95th percentile of torso length. The distance between the waist and cervical vertebrae of the back neck ranges from 55.97 to 67.80 cm in males, and from 54.11 to 62.96 cm in females. Also, female firefighters have narrower shoulder widths than males, which makes it easier for their shoulder straps to slide. The bust dimensions of female firefighters are also different from that of males, which means the chest strap from the SCBA harness may land in an uncomfortable place (Lee et al., 2015).

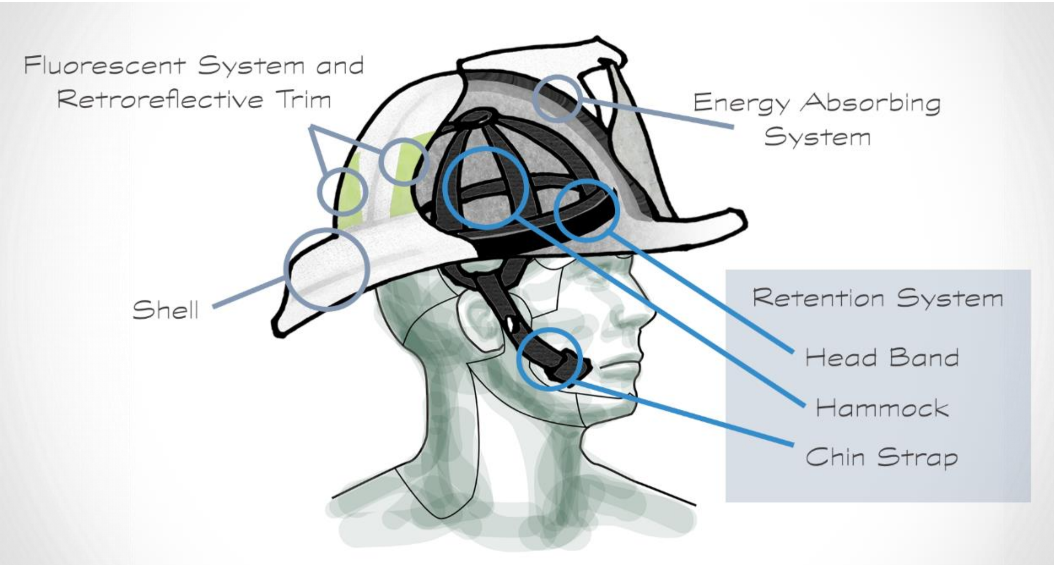
With the above in mind, adding more fit-optimizing design factors can be a consideration for reducing the discomfort caused by the poor weight distribution and wrong placement of the SCBA harness. This may also improve firefighters' upper body ROM. Besides, compatibility with other fire gear should be considered to maximize the functionality of each PPE item. In the case of female firefighters, chest strap placement is an additional concern; inadequate strap positions can impose more pressure on the bust area, inducing shoulder movement restrictions and discomfort (Lee et al., 2015).

2.2 Fire Helmet Design Issues

Securing a clear and wide range of vision is important for protecting firefighters from obstacles and injuries during hazardous firefighting situations. Paulus et al. (1984) noted that securing a clear vision affects postural control and, especially, the loss of vision can increase postural instability. Vision plays an important role in maintaining body balance in situations of instability in the face of proprioceptive sensations (Colledge et al., 1994). Even though securing visual input is important for body balance control, which is closely related to slip and fall risks, firefighting is usually performed in poor visibility environments (Punakallio, 2005). In addition, wearing a fire helmet can have a further negative impact on firefighters' vision by limiting the neck ROM, due to its wide brim and bulky shape, which contribute to a poor gait balance (Lee et al., 2015; Park et al., 2014). According to NFPA 1971 standards (2018), the structural fire helmet consists of a shell, energy absorbing system, retention system, fluorescent system and retroreflective trim, ear covers, and a face shield or goggles. All of these elements are designed for head protection (Figure 4).

Figure 4

Components of a Structural Fire Helmet



Even though helmet designs vary slightly by country and manufacturer, and depending on their tactical use (Lee et al., 2014), the fire helmet shell is manufactured using only one size mold. Furthermore, the shell is made of stiff material, in a bulky shape and with along brim for head and neck protection against external impacts. The long, wide brim of the helmet can negatively affect a firefighter's vision (Lee et al., 2014; Lee et al., 2015). Fire helmets allow space between the helmet shell and hammock, as an energy-absorbing function against exterior collisions; thus, it seems inevitable that the bulky shape of the fire helmet must be maintained to allow gaps between the helmet's outer shell and the firefighter's head, for safety reasons.

The long-term use of a fire helmet can cause chronic neck pain, and the weight of the front shield and wide brim of the helmet adds load to the cervical spine (Barker et al., 2012; Lee et al., 2015). Although the stable placement of the helmet on the head is important considering firefighters' active movements, the hanging system of the conventional fire helmet is designed to be fit-adjustable only at the headband and chin strap, while the retention part remains weak for securing the weighty helmet to the individual's head. Previous studies have noted the ill-fit of fire helmets, especially in terms of inner fit and the poor placement of helmet straps (Lee et al., 2015). The fit issue should be considered for improving helmet design (Park et al., 2014). One firefighter commented on the poor fit of the helmet and face mask:

> "When I have my mask on, I can't push my helmet down where its comfortable so I feel like it's sitting up higher on my head and I have to crank my chin strap down to keep it from falling off and it just doesn't marry up well on my face, and it's probably because my face is smaller." (Park et al., 2014, p. 9)

In addition, a national report (U.S.) about women in firefighting stated that, among all PPE items, complaints regarding the poor fit of the helmet constituted 28.4% (Hulett et al., 2008). Another previous study stated that the uneven compression and uncomfortable feel of the helmet can be reduced while still maximizing the protective function of the helmet by providing a proper fit (Liu et al., 2008). Even though a length-adjustable headband already exists in the current helmet retention system, the head contact area of the band is limited only in terms of head circumference.

Firefighters have a wide range of head circumferences and dimensions. Body measurement data from the NIOSH indicate that 95% of male firefighters' head circumferences are in the range of 55 to 60.9 cm (57.8 cm in the 50^{th} percentile) and, in the case of females, the range is between 53.2 and 59.2 cm (55.7 cm in the 50^{th} percentile). In terms of head arc, the 95th percentile is between 32.3 and 39.2 cm (35.5 cm in the 50^{th} percentile), and 30.2 and 38.5 cm (34.5 cm in the 50^{th} percentile), respectively, for males and females. However, the range of size-adjustable headband circumferences is between 60 and 75 cm, in the case of the Morning Pride Ben 2 helmet, a conventional model used in this study as a control helmet design. The length of the liner covering the head arc inside the helmet was 34 cm. Simply fit-adjusting only for head circumference may not be enough to secure the fire helmet to the head when also considering the bulky shape and heavy weight of the helmet during a firefighter's dynamic neck movements. Therefore, attempts to improve the helmet design to provide an optimal fit and compatibility among gear should be meaningful enough to minimize discomfort and limitations in neck ROM brought on by the fire helmet.

CHAPTER 3

Methods

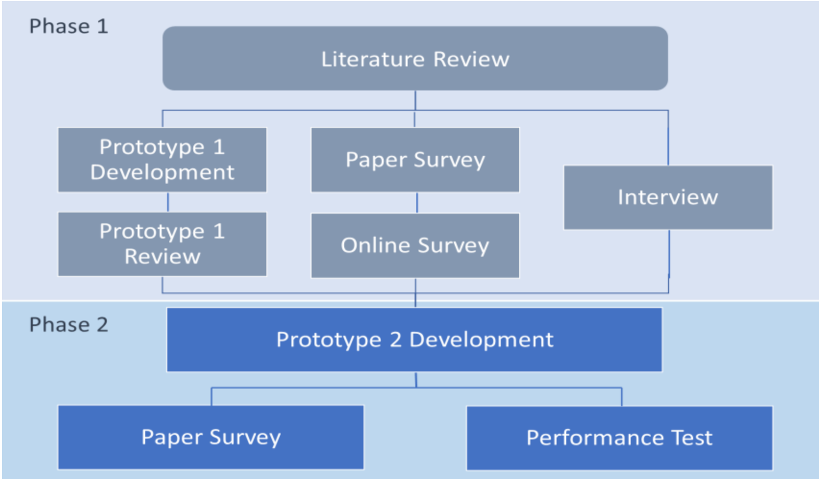
This chapter consists of two phases (see Figure 5). The first phase focuses on the development of the first prototypes for a new SCBA harness and firefighting helmet. It includes empirical data collected to identify design issues related to the harness and helmet. In the second phase, second versions of the prototypes were developed, based on the empirical feedback gathered in Phase 1. The design validity of the second prototypes was evaluated. All interviews, surveys, and human performance tests used in this study were conducted under the approval of the Institutional Review Board (see Appendix 1).

3. 1 Phase Ⅰ: Design Development of Compatible Firefighters' PPE

Phase 1 included the design development process for the first prototype of the SCBA harness and firefighting helmet and data collection, to identify problems related to the current harness and helmet design. To obtain firefighters' input on current fire gear designs and their feedback on the first prototypes, two types of surveys; prior to online survey paper survey was developed and conducted with local firefighters, were developed and semi-structured interviews were conducted. The surveys were used to identify the characteristics of current PPE designs, while the interviews aimed to elicit design suggestions and reviews of the prototypes. Interviews were conducted either one-on-one or in a group setting, depending on participants' time availability; all were video- and audio-recorded with the participants' consent.

Figure 5

Prototype Development and Evaluation Process



To collect empirical feedback in an in-person set (from interviews and the paper survey), seven firefighters (3 men and 4 women) were recruited from a local fire department in New York. For the online survey, 93 firefighters (66 men and 27 women) were recruited throughout the United States. All the participants have experienced wearing and using firefighting PPE for at least six months. The demographic data of participants are described in Table 2.

Table 2

Demographic Details for Research Participants in Phase 1

Index	Gender	Interviews & Paper Survey (Seven Firefighters (NY))		Online Survey er (Ninety-three Firefighters)	
		Mean	SD	Mean	SD
Age (yrs)	Female	23.50	3.87	38.81	9.49
	Male	27.00	10.39	40.02	12.30
Height (cm)	Female	162.56	9.95	165.71	6.03
	Male	180.23	5.08	179.46	6.00
Weight (kg)	Female	72.25	9.84	1.28	14.80
	Male	71.79	6.57	94.59	16.75
BMI	Female	22.07	1.05	27.94	5.67
	Male	27.61	5.59	29.32	4.61
Duration of Service (yrs)	Female	2.30	1.32	13.83	7.69
	Male	4.50	1.12	15.21	11.63

3. 1. 1 Development of Prototype 1

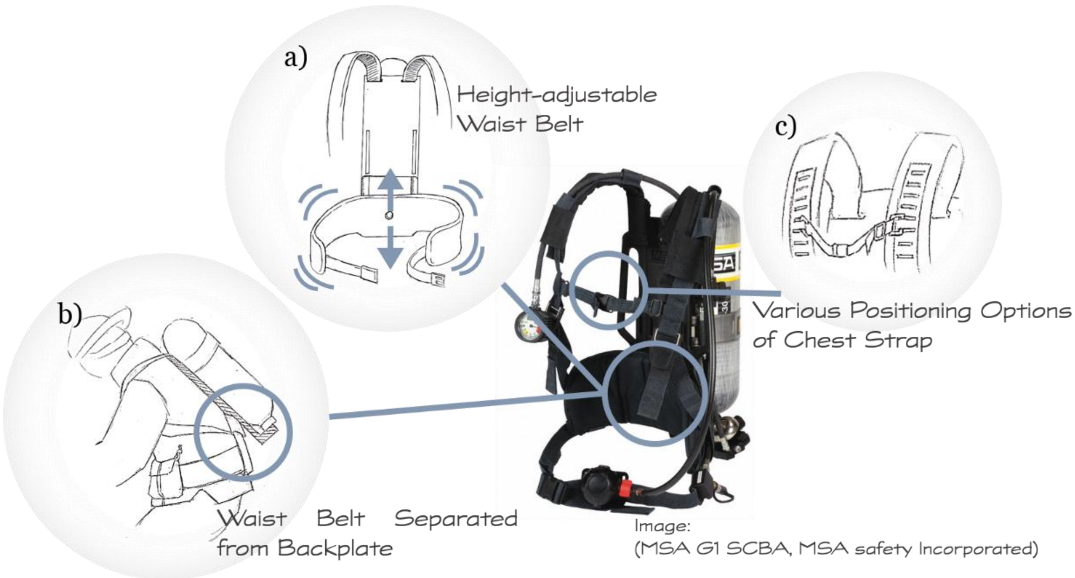
Prior to the empirical data collection, the first prototypes of the SCBA harness and helmet were developed based on the consideration of design issues mentioned in the literature review. The design requirements of the NFPA (2018) 1971 Standards were reviewed. The prototype designs developed in this study comply with the design requirements and guidelines from NFPA 1971.

3. 1. 1. 1 Development of SCBA Harness Prototype 1

For the fit optimization of an SCBA harness for the upper body, three main design issues were addressed: a height-adjustable waist belt, separating the waist belt and lower part of the back plate, and a height-adjustable chest strap (Figure 6).

Figure 6

The Main Design Concepts of SCBA Harness Prototype 1



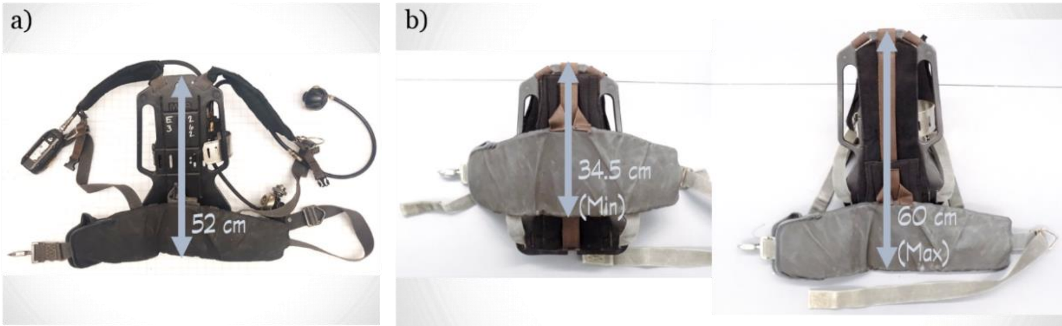
The first area for the redesign was the height-adjustable waist belt, to make it possible to position the belt at the laterally proper position for a given individual (Figure 6a). A height-adjustable waist belt is needed so that each firefighter, regardless of torso length, can carry the SCBA weight efficiently and without limiting their neck ROM.

The current SCBA was designed only to adjust the height of the harness to fit the body trunk via shoulder straps. However, only adjusting the shoulder straps cannot secure enough space for neck movements, thus visibility is negatively affected. A height-adjustable waist belt can alleviate this problem. By maintaining the air tank at a comparatively constant height with the height-adjustable waist belt, it is expected that firefighters will be able to secure enough space between the helmet and the top of the air tank, regardless of the widely varying range of individuals' torso lengths. Consequently, all firefighters will be able to maintain the air tank at a low position, near the waist and pelvis, making it easier to carry the load. As Figure 7 shows, whereas the conventional backplate design has a fixed length (52 cm) between the top of the plate and the waist belt (a), the first SCBA prototype has a height-adjustable range of 25.5 cm (min: 34.5 cm, max: 60 cm) on the back plate (b). According to SizeUSA data (TC^2 Inc), a national anthropometric data including 3647 of U.S. males, this range can accommodate 99.59% of males' backs, so that the height-adjustable waist belt may be placed at the optimal height for each person's waist. In the case of female data (n= 6813), the height-adjustable range accommodates 99.99% of females' back lengths. Hook-and-loop fasteners were used on the SCBA back plate to set the waist belt to the desired height.

Next, the waist belt was redesigned to be separate from the lower part of the back plate, intending to increase the degree of freedom in lumbopelvic flexion motion (Figure 6b). Separating the waist belt from the back plate was also intended as a means of facilitating the rotation following the pelvis movement for gait.

Figure 7

(a) Fixed Position of a Conventional SCBA; (b) Height-adjustable Waist Belt of Prototype 1



The third design point focused on the chest strap. Height options for chest strap placement were added to allow for the optimal placement of the strap on the individual's body (Figure 6c). Sometimes, an inappropriately placed chest strap can induce ill fit on the wearer's chest area and restrict mobility around the shoulder and arm. In addition, the chest strap can block access to the chest pocket of the turnout coat. The placement of the chest strap is easily moveable by changing the height of the buckles on the edge of the strap while connecting the buckle to the hoops on the shoulder straps.

3. 1. 1. 2 Development of Fire Helmet Prototype 1

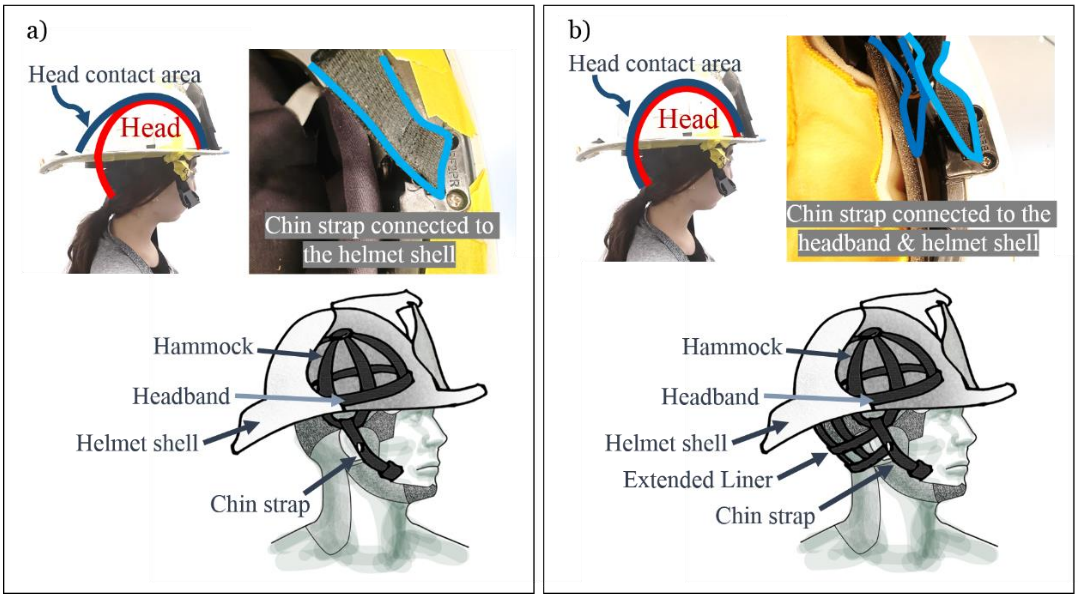
In this study, redesigning the helmet's head retention system was focused on providing secure wear and stable fit of the helmet. Although it is still necessary to allow some gaps between the head and the helmet shell for safety reasons, the gap may intensify a looser or unstable fit of the helmet. To improve the fit, fit-adjustable design components were added to the helmet retention system.

Extending the head contact area of the helmet was the distinctive point of the prototype design, compared to the conventional helmet retention design. In a conventional helmet, the chin strap and headband are the only fit-adjustable components, and the headband and hammock are the only components of the retention system used to secure the helmet to the head. As shown in Figure 8a, the hammock of a conventional fire helmet is in contact only with the upper head area; it does not fully retain the nape or lower crown area of the head.

To improve the hanging system, the helmet's hammock was extended on the lower head in Prototype 1. In this study, the extended hammock is called the "extended liner". Adding the liner not only makes it possible to secure the helmet on

Figure 8

The Main Design Concepts of Fire Helmet Prototype 1



the head, but it also prevents the helmet's brim from obscuring the firefighter's sight, by keeping the helmet from falling during a neck flexion or extension. The prototype's extended liner was designed to cover the lower part of the head's crown and partial areas of the nape of the neck; the conventional helmet hammock only covers the top of the head's crown area (see Figures 8b and 9). In the conventional helmet design, the wearer can adjust the fit only with the headband and chin strap. However, in the prototype design, a web of elastic straps was added as the extended liner, and each strap in the web can be length-adjusted with hook-and-loop fasteners, as seen in Figure 8b.

Figure 9

The Conventional Helmet (left) and Helmet Prototype 1 (right)

3. 1. 2 Empirical Data Collection of Firefighters' PPE Design Issues

The empirical feedback collected in this phase aimed to be actively applied in the development of the second prototypes, in Phase 2. The feedback data collection consisted of the paper and online surveys on the design issues related to conventional gear; semi-structured interviews elicited new design suggestions and gathered reviews on the first prototypes.

3. 1. 2. 1 Data Collection for Empirical Feedback of Conventional PPE Design

The survey sought to identify the design problems and issues related to the conventional SCBA harness and fire helmet design, from the firefighters' point of view. To collect these data, a two-step survey was conducted. First, a paper survey was distributed to seven firefighters before a larger online survey was distributed among firefighters throughout the U.S. The surveys covered design issues mainly related to the two kinds of PPE addressed in this work (the SCBA harness and helmet), and partially addressed the pockets on turnout gear to figure out the impact of harness design on the use of pockets on turnout ensemble. The survey topics dealt with how well the current size chart reflects firefighters' general anthropometric features, to what extent the firefighters are satisfied with the fit of their current PPE, and how comfortable the firefighters feel while wearing their current PPE (Table 3). The surveys used a seven-point Likert scale (possible answers ranged from -3: strongly disagree/dissatisfied to 3: strongly agree/satisfied) and short answer questions in support of the Likert scale questions. Seven firefighters from the local fire department completed the paper survey. Only the mean value and standard deviation of raw data were calculated due to the small sample size (n = 7) in respect of the data obtained by the paper survey. In the online survey, Qualtrics (Qualtrics, Provo, UT) survey software was utilized and the survey link was shared to fire departments throughout the U.S by contacting one by one. A two-tailed *t*-test was performed in the online survey with .05, 0.1, 0.01 significance levels to assess the difference in satisfaction between male and female firefighters in using the current harness and helmet design. Furthermore, the correlation between satisfaction and height was evaluated to determine whether the height is a factor influencing satisfaction.

3. 1. 2. 2 Data Collection for Empirical Suggestion of Improving PPE Design

The purpose of the semi-structured interviews was to elicit participants' ideas in a free and open atmosphere for new SCBA harness and helmet designs while considering human factors. The participants were asked to suggest and develop their ideas to improve the PPE design based on their field experience and practical needs

Table 3

Online Survey Questions of Conventional PPE Design

Gear	Questions
	Sizing System
SCBA	Can you easily find the right fit of SCBA (SCBA harness)?
	The fitting system is well-considering individuals' anthropometrical differences?
	The fitting system is well-considering individuals' anthropometrical differences by gender?
	Fit
	Are you satisfied with the fit of your current SCBA?
	Are you satisfied with the shoulder strap design of SCBA?
	Are you able to adjust the shoulder strap of SCBA to fit your body?
	Are you satisfied with the back-plate design of SCBA?
	Are you satisfied with the length of back-plate?
	Are you able to adjust the SCBA to fit your torso length.
	Are you able to adjust the SCBA to fit your torso width.
	Are you satisfied with the waist belt design of SCBA?
	Are you able to adjust the waist belt of SCBA to fit your waist and pelvis.
	Your current SCBA has the chest strap?
	If you said "Yes", are you satisfied with the chest strap design of SCBA?
	If you said "Yes", are you able to adjust the chest strap of SCBA to fit your chest or bust?
	Do you feel that any parts of the SCBA are tight? (If you said "tight", what is the part and why?)
	Do you feel that any parts of the SCBA are loose? (If you said "loose", what is the part and why?)
	Do you think you need additional size adjustment mechanism for SCBA or SCBA harness? (If you said that the additional size adjustment mechanism is needed, which part of the SCBA should be size adjustable and what is the reason?)
	Wearer Comfort
	When you wear your SCBA, the fit is comfortable?
	When you bend your neck backward, the SCBA works well with the firefighting helmet?
	Do you feel that any parts of the SCBA are discomfort?
Pockets (Turnout ensemble, SCBA harness)	Are you satisfied with the placement of the pockets on your turnout coat?
	Are you satisfied with the placement of the pockets on your turnout pants?
	Are you easily able to access/open the pockets during your duty?
	Are you satisfied with the storage capacity of the pocket for your firefighting tools?
	Do you think the SCBA harness blocks the opening of the pocket?
	Are you satisfied with the fixing system for the firefighting tools on the pocket inside?

Gear	Questions
	Sizing System
	Can you easily find the right size of firefighting helmet?
	The size chart is well-considering individuals' anthropometrical differences?
	The size chart is well-considering individuals' anthropometrical differences by gender?
	Fit
	Are you satisfied with the fit of your current helmet?
	Are you satisfied with the headband design of your current helmet?
	Are you able to adjust the headband of the helmet to fit your head circumference?
	Are you satisfied with the hammock design of your current helmet?
Fire Helmet	Are you able to adjust the hammock of the helmet to fit your head shape?
	Are you satisfied with the chin strap design of your current helmet?
	Are you able to adjust the chin strap of the helmet to fit your head and face?
	Do you feel that any parts of the helmet are tight?
	Do you feel that any parts of the helmet are loose?
	Do you think you need additional size adjustment mechanism for firefighting helmet?
	Wearer Comfort
	When you wear your firefighting helmet, the fit is comfortable?
	Do you feel that any parts of the helmet are discomfort?
	The helmet can be stably fixed on your head while doing neck motion (such as bending neck forward, backward, or lateral bending)
	The helmet works well with the firefighting face mask?

while firefighting. The discussion topics for the design suggestions largely consisted of fit, design, positioning, wearability, and general likes and dislikes related to the SCBA harness and helmet (Table 4).

3. 1. 2. 3 Data Collection for Empirical Review of Prototype 1

The prototype review aimed to evoke participants' specific and precise feedback on using the prototype SCBA harness and fire helmet based on their field experience. Participants were asked to share their opinions and discuss their concerns about the first prototype designs in a free and open atmosphere. Both

Table 4
Interview Outline and Discussion Topics for PPE Design Improvement

Gear	Topics
SCBA	**Fit** Would you like to adjust the size or length of any parts of the SCBA? Please discuss the design solution to improve the size adjustment mechanism of the SCBA. What positive/ adverse effect you can expect by adding the size/length adjustability on the SCBA? **Design** Are you satisfied with the SCBA' donning/doffing system? Are you satisfied with the SCBA' closure system? What are you think about SCBA's carrying design? Is SCBA well designed to work with the turnout coat/pants? Is SCBA well designed to work with the pockets on turnout coat/pants? Is SCBA well designed to work with the helmet? Is there any performance limitation from the SCBA? Are there any working errors from an unfavorable fit of SCBA? What can be the design solution to reduce the errors? **Placement (Positioning)** Which SCBA design element would you like to be able to customize in terms of placement? Which design elements of the SCBA would you like to able to attach or remove? Wearer Comfort Do the SCBA feel stable on your body while you are performing your firefighting duties on fireground? Like & Dislike Please discuss the design elements you like on the SCBA. Are you satisfied with wearing the SCBA? Please discuss the design elements you dislike on the SCBA.
Pocket (Turnout Ensemble, SCBA harness)	Do you have any problem to use the pockets on turnout gears (coat and pants)? What can be the design solution to improve the accessibility to pockets. What do you think about if the pockets on the turnout coat are attachable (not affixed on the coat)? What can be the design solution to improve the fixing ability of the pockets for your firefighting tools?
Fire Helmet	**Fit** Please discuss the design solution to improve the size adjustment mechanism of the helmet. Design Are you satisfied with the helmet's donning/doffing system? Are you satisfied with the helmet's closure system? Are you satisfied with the helmet's liner design? What are you think about the helmet's hanging system? Is the helmet well designed to work with the mask? Is the helmet well designed to work with the hood? Placement (Positioning) Which helmet design element would you like to be able to customize in terms of placement? Which design elements of the helmet would you like to be able to attach or remove?
Fire Helmet	**Wearer Comfort** Does the helmet feel stable on your head while you are performing your firefighting duties on fireground? Like & Dislike Please discuss the design elements you like on the helmet. Are you satisfied with wearing the helmet? Please discuss the design elements you dislike on the helmet.

prototypes and conventional PPE were provided to the participants, for their easy comparison of the designs. During the review, participants tried the prototypes on and tested the wearability, ease of fit-adjustment, and ease of donning and doffing.

3. 2 Phase Ⅱ: Design Development and Evaluation of Compatible Firefighters' PPE

Phase 2 included the design development of the second prototype and an evaluation of the designs. The design evaluation aimed to assess how the added fit-optimizing design affects firefighters' upper body movement and satisfaction in wear. To evaluate the second prototype designs, a paper survey and human performance tests were conducted with the participation of 8 firefighters (6 men and 2 women) from local fire departments (NY). All participants have at least six months' experience wearing and using firefighting PPE. Six male firefighters, with an average age of 28.83 ± 10.21 years, an average height of 182.46 ± 4.93 cm, an average weight of 91.85 ± 14.40 kg, an average body mass index (BMI) of 27.54 ± 3.82, and average duration of service 7.33 ± 7.31 years participated. In addition, two female firefighters with an average age of 23.5 ± 3.54 years, the height of 165.1 ± 0 cm, the weight of 72.57 ± 6.41 kg, BMI of 26.63 ± 2.35, and duration of service of 2 ± 1.41 years comprised the study participants.

3. 2. 1 Development of Prototype 2

The second version of the SCBA harness and fire helmet prototypes was developed based on empirical feedback gathered in Phase 1. While the first prototype design was focused on functional development, the second design was mainly focused on user convenience in using the prototypes while keeping the basic functional design concepts of Prototype 1.

3. 2. 1. 1 Development of SCBA Harness Prototype 2

In the second prototype of the SCBA harness system, the basic design concepts of a height-adjustable waist belt and releasing the lower back from the back plate were maintained. One big difference between the first and second prototypes was whether the waist belt should be held at a certain height. The hook-and-loop fastening system for the height-adjustable waist belt in Prototype 1 required an additional procedure to adjust for height and to fix the belt at a certain level before donning the SCBA. According to the NFPA *1001 Standard for Firefighter Professional Qualification* (2012), the SCBA should be donned within one minute for use in an emergency, regardless of what the SCBA donning method is (over-the-head, coat, or seat-mounted method), and all straps and components of the SCBA should be returned back to the ready state for another immediate use after use of the SCBA. The additional procedure needed for Prototype 1's donning and doffing system for adjusting and returning the height of the waist belt is not a proper design approach for emergent rescue and firefighting situations.

With the above in mind, when designing the second prototype, easy height-adjustment of the waist belt and quick donning and doffing methods should be included. In the second SCBA prototype, a sliding device was mounted on the back plate, replacing the hook-and-loop fastener. With this new device, firefighters can easily adjust the height of the waist belt by pulling the belt upward or downward (Figure 10). As seen in Figure 11a, the length-adjustable range of this prototype increased to 30 cm (min.: 28 cm, max.: 58 cm) on the back plate, while the range of the previous prototype was 25.5 cm (min.: 34.5 cm, max.: 60 cm).

Furthermore, to accommodate the changing torso dimensions of different upper body postures, the height of the waist belt in Prototype 2 was designed to be

Figure 10

Sliding Device of the Height-adjustable Waist Belt

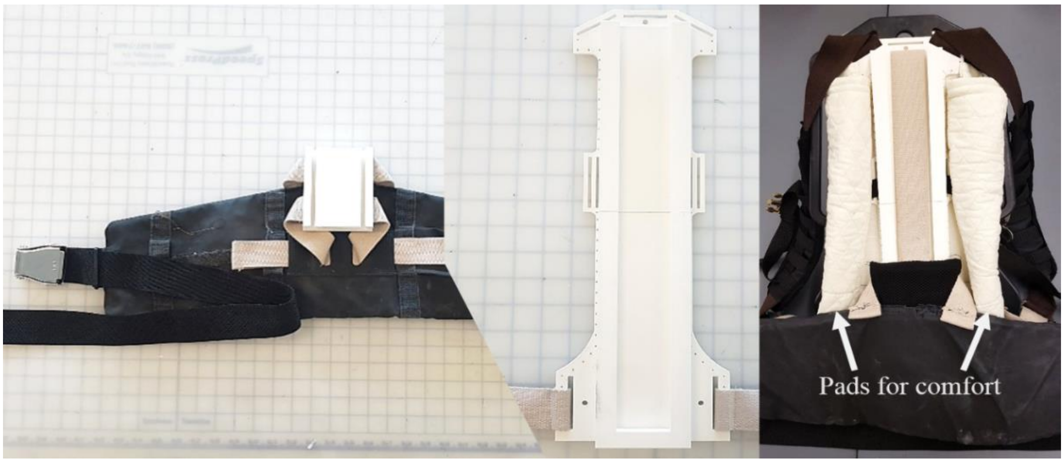
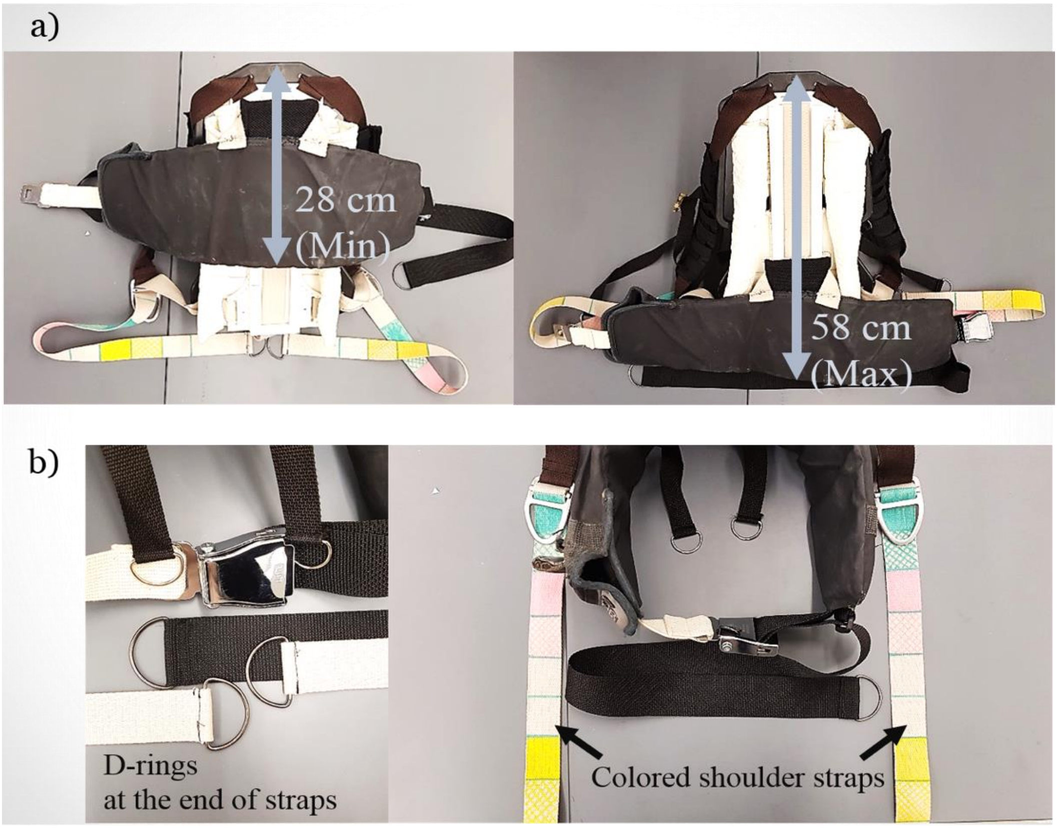


Figure 11

The Height-adjustable Range of Prototype 2 (a) and Other Design Details (b)



vertically moveable, instead of being fixed in a certain position. It is important to remember that an individual’s torso length can be changed by their posture; for example, the torso length is different while standing up straight or bending the back.

Usually, the weight of the SCBA is supported by the pelvis and shoulders when in a standing posture. However, during lumbopelvic flexion, the weight of the SCBA is supported by the back, not the pelvis. This can mean that a belt firmly fixed at the waist can be an obstacle for waist-bending motions while also failing to support the weight of the SCBA. It is expected that the waist belt should be placed at the optimal height to fit each posture.

Straps: The use of an SCBA harness with thick and bulky firefighting gloves was also considered for enhancement, in terms of the convenience of use. The type of buckle used in the waist belt was changed to one like that used in seatbelts, for easier operation. At the edge of each strap of the SCBA harness, D-shaped rings were added to make it easier to grab while wearing gloves (Figure 11b).

Shoulder straps: Each shoulder strap was color-coded to distinguish its length per 5 cm. This can help firefighters to don the SCBA harness correctly, with a consistent strap length and balanced donning on each shoulder (Figure 11b).

3. 2. 1. 2 Development of Fire Helmet Prototype 2

When designing the prototype of the second firefighting helmet, the basic design concept of the extended and fit-adjustable liner was maintained. In the first prototype, it took considerable time and effort to adjust the fit of the liner during the donning procedure. Thus, in the second prototype, a Boa dial was adopted to adjust the fit more quickly and easily in an emergent situation. This also allows firefighters to put on the helmet while wearing thick gloves. The Boa dial was identified as an effective substitute for typical closure systems such as laces, ratchets, and hook-and-loop fasteners because the dial can make it easier to tighten and loosen a strap by simply turning the dial clockwise or counter-clockwise (Bont Skates Online Shop, 2019). A lining-layered sport nylon was selected as the material for the Boa dial plate (Figure 12). The shape of the plate can easily distort single-layered fabric when turning the Boa dial, so an interlining was added between the two layers of fabric to enhance the stiffness of the plate.

Figure 12

The Second Helmet Prototype

3. 2. 2 Design Evaluation Method of Prototype 2

The design evaluation consisted of 3D body scanning and a paper survey on general upper body movement, to evaluate firefighters' satisfaction with the use of the redesigned PPE.

The test for the design evaluation of Prototype 2 included two independent variables and two dependent variables, and the order of trial was randomly assigned (see Table 5).

Table 5

Independent Variables and Testing Groups

Trial	Set-One		Set-Two	
Type	Conventional PPE (SCBA harness and helmet)		Prototype 2 (SCBA harness and helmet)	
Gender	Male	Female	Male	Female

The first independent variable is the type of PPE design on two levels, the conventional PPE design and Prototype 2. The second independent variable is the gender group (male and female), to investigate the extent to which the prototype designs can cover male and female firefighters' bodies properly, compared to conventional designs. This experiment was designed as a within-group study, which can reduce errors stemming from individual differences and due to the small pool of participants (Cherry, 2019).

To assess firefighters' satisfaction with the use of PPE, donning and doffing times were measured, and a paper survey was conducted to inquire about the prototype's ease of use, the ease of donning and doffing, the convenience of use, fit satisfaction, and the compression from the SCBA harness and helmet (Table 6). To gather subjective feedback regarding the changes in the upper body movements related to the type of PPE, the paper survey also asked about upper body mobility. Two types of paper survey were prepared for each of the control and treatment test sets. The paper survey's questions used a seven-point Likert scale, with answers ranging from -3: strongly disagree/dissatisfied to 3: strongly agree/satisfied. For design evaluation through the paper survey, a paired sample *t*-test was used in the statistical analysis to determine whether the mean difference between the satisfactions in use of the conventional designs and prototype designs of the observations is zero.

To assess the changes in upper body performance by type of gear (conventional gear vs. Prototype 2), 3D body scanning was conducted to analyze static upper body ROM. The ROM was analyzed with parametric or non-parametric analysis. In this stage, only males' data (n = 6) were analyzed, because it was difficult to elicit valid statistical results with the females' data, due to the small

Table 6

Questions for Design Evaluation of Prototype 2 Designs

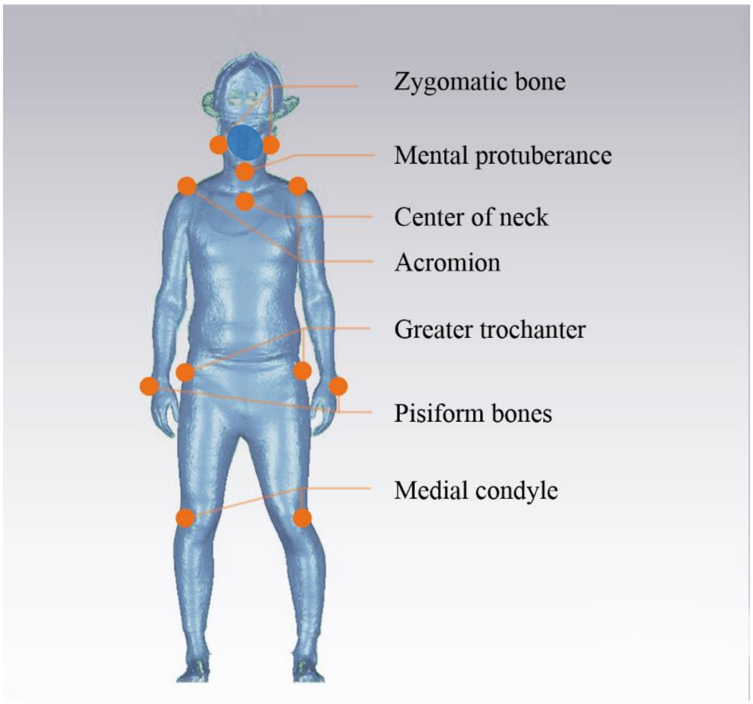
Gear		Questions
SCBA	Ease of donning and doffing	Donning Time (sec)
		Doffing Time (sec)
		Ease of donning
		Ease of doffing
	Convenience of use	Ease of access to shoulder straps for length-adjustment
		Ease of length-adjusting shoulder straps
		Ease of assessment of length-adjustment and balance of shoulder straps
		Ease of access to waist belt for length-adjustment
		Ease of length-adjusting waist belt
		Ease of assessment of length-adjustment of waist belt
		Ease of access to backplate for height adjustment of waist belt
		Ease of height-adjusting the waist belt on backplate
		Ease of assessment of height of waist belt on backplate
	Wearing Comfort	Satisfaction of wearing comfort from weight of SCBA
		Satisfaction of wearing comfort from general fit of SCBA
		Stability of wearing SCBA
		Satisfaction of compression from fit of SCBA
	Upper-body movement	Agreement on no restriction of general body movement with SCBA
		Agreement on no restriction of lumbopelvic flexion movement with SCBA
		Agreement on no restriction of lateral flexion movement with SCBA
		Compatibility with fire helmet in neck motion
		Agreement on no restriction of mobility
Fire Helmet	Ease of donning and doffing	Donning Time (sec)
		Doffing Time (sec)
		Ease of Donning
		Ease of doffing
	Convenience of use	Ease of access to chin strap for length-adjustment
		Ease of length-adjusting chin strap
		Ease of access to extended liner for fit-adjustment
		Ease of fit-adjustment of extended liner
	Wearing Comfort	Satisfaction of wearing comfort from weight of helmet
		Satisfaction of wearing comfort from general fit of helmet
		Stability of wearing helmet
		Satisfaction of compression from fit of helmet
	Neck Movement	Agreement on no restriction of general neck movement with helmet
		Degree of matching of helmet and neck movements

sample size (n = 2). Prior to analyzing the static ROM of male participants, the Shapiro-Wilk test of normality was conducted to verify whether the data were normally distributed for a parametric analysis procedure. Then, a paired sample *t*-test was performed for the data valid for a parametric analysis or a Wilcoxon signed-rank test was performed for a nonparametric analysis.

All participants were asked to wear fitted, sleeveless tops and tights as the baseline garment. This ensured we could completely scan all postures. For the 3D body scanning, retroreflective markers were placed on the zygomatic bone, the mental protuberance, the center of the neck, acromion, greater trochanter, pisiform bones, and medial condyle, to measure the static ROM (Figure 13). A total of 11 postures (4 for the helmet, 7 for SCBA) were assigned to analyze the ROM, and the scan for each posture was repeated three times by each participant, to determine the reliability of the 3D scan measures.

Figure 13

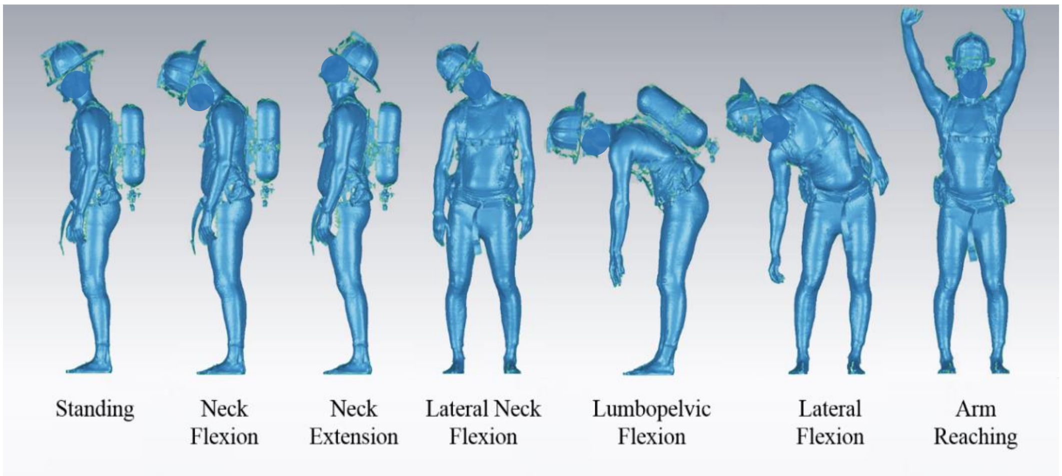
Placement of Retroreflective Markers



SCBA-related postures: Participants were asked to perform seven postures while wearing the two types of helmet and SCBA harness (conventional and Prototype 2), as shown in Figure 14. Each posture was selected for the following intentions:

Figure 14

Upper Body Postures for Evaluating SCBA Designs



- Standing: Reference posture of neck movement, and to check the relationship between the vertical position of the air cylinder and neck extension
- Neck Flexion: To check the ROM of the neck on flexion
- Neck Extension: To check the ROM of the neck on extension and the relationship of the vertical position of the air cylinder and neck extension
- Lateral Neck Flexion: To check the ROM of the neck on lateral neck flexion
- Lateral Flexion: To check the effects of separating the waist belt from the back plate on the back-bending posture
- Lumbopelvic Flexion: To check the effects of separating the waist belt from the back plate and unfixed waist belt design on the back-bending posture

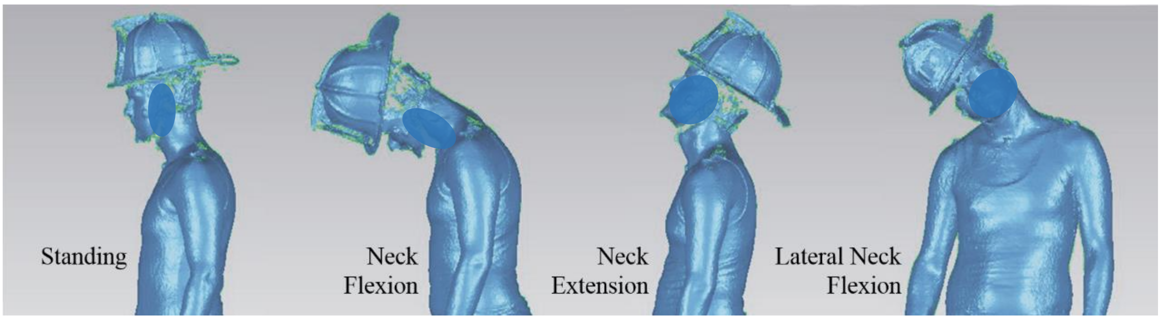
  Arm Reaching: To check the effect of the unfixed waist belt on shoulder movement

Helmet-related postures: Participants were asked to perform four helmet-related postures while wearing the two types of the helmet (conventional and Prototype 2) to evaluate the effects of the type of helmet on the fit of the helmet and neck movement (Figure 15). Each posture was selected for the following intentions:

- Standing: Reference posture of neck movement
- Neck Flexion, extension, and lateral flexion: To determine how helmet movement is matched with the wearer's head movement

Figure 15

Neck Movement Postures for Evaluating Helmet Designs



CHAPTER 4

Results and Discussion

This chapter consists of the sections regarding results and discussion. First, the findings of this study were stated. Then, the summary and the interpretation of the findings were given at the end of each phase.

4. 1 Phase Ⅰ: Design Development of Firefighters' PPE for Improved Compatibility

4. 1. 1 Empirical Review of Conventional Firefighters' PPE Design

4. 1. 1. 1 Review of SCBA Design

Paper Survey with 7 Firefighters

SCBA

Table 7 shows 7 firefighters' feedback on the sizing system, fit, and wearing comfort of a conventional SCBA harness. A female firefighter whose height is 152 cm generally recorded negative responses regarding the sizing system, fit, and wearing comfort of the SCBA while a male firefighter whose height is 185 cm positively responded to the same questions. In wearing comfort, six of seven participants appeared to experience discomfort when using an SCBA and all the six's height was below 185 cm. Regarding the participants' satisfaction in the current sizing system of the SCBA harness, three out of four female participants agreed that the current sizing system is less comfortable when considering the differences in body size and shape by gender, while one out of three male participants agreed with this statement. Regarding the fit of the SCBA harness, the male participants were satisfied with the overall fit. In the case of the female participants, two out of four were satisfied with the overall fit, while the other half did not complain about a loose

Table 7

Means and Standard Deviations of Ratings of Evaluation of Conventional SCBA Design

Design issue		height (cm)	Female						Male				
			Under 160		160 ~ 170	Over 170	Mean	SD	170 ~ 180	Over 180		Mean	SD
			152	157	165	175			175	180	185		
Sizing system	Can you easily find the right fit of SCBA harness?		-3	3	0	3	0.75	2.87	3	2	2	2.33	0.58
	The fitting system is well-considering individual's anthropometrical differences?		-3	1	-2	1	-0.75	2.06	2	2	1	1.67	0.58
	The fitting system is well-considering the anthropometrical differences by gender?		-3	-1	0	-1	-1.25	1.26	0	2	0	0.67	1.15
Fit	Are you satisfied with the fit of your current SCBA?		-3	2	-2	2	-0.25	2.63	2	1	2	1.67	0.58
	Are you satisfied with the shoulder strap design of SCBA?		-3	3	2	2	1.00	2.71	-1	-1	1	-0.33	1.15
	Are you able to adjust the shoulder strap of SCBA to fit your body?		-2	1	2	3	1.00	2.16	2	2	2	2.00	0.00
	Are you satisfied with the back-plate design of SCBA?		0	2	0	1	0.75	0.96	2	2	2	2.00	0.00
	Are you satisfied with the length of back-plate?		-2	2	0	2	0.50	1.91	2	1	2	1.67	0.58
	Are you able to adjust the SCBA to fit your torso length?		-3	1	2	2	0.50	2.38	2	2	2	2.00	0.00
	Are you able to adjust the SCBA to fit your torso width?		-3	2	-2	2	-0.25	2.63	2	2	2	2.00	0.00
	Are you satisfied with the waist belt design of SCBA?		-3	2	-2	2	-0.25	2.63	-1	-1	3	0.33	2.31
	Are you able to adjust the waist belt of SCBA to fit your waist and pelvis?		-3	-1	-2	2	-1.00	2.16	2	0	3	1.67	1.53
	Your current SCBA has the chest strap?		yes	no	yes	no	-	-	no	no	no	-	-
	Are you satisfied with the chest strap design of SCBA?		0	-	6	-	3.00	1.41	-	-	-	-	-
	Are you able to adjust the chest strap of SCBA to fit your chest or bust?		-1	-	6	-	2.50	2.12	-	-	-	-	-
	Do you feel that any parts of the SCBA are tight?		-3	-2	-2	-1	-2.00	0.82	-2	-2	-2	-2.00	0.00
	Do you feel that any parts of the SCBA are loose?		3	2	2	-1	1.50	1.73	-2	-1	-2	-1.67	0.58
	Do you think you need additional size adjustment mechanism for SCBA?		3	0	2	-1	1.00	1.83	2	-2	-1	-0.33	2.08
Wear Comfort	When you wear your SCBA, the fit is comfortable?		-3	1	-2	1	-0.75	2.06	1	-1	2	0.67	1.53
	When you bend your head backward, the SCBA works well with the firefighting helmet?		-3	-2	-2	-1	-2.00	0.82	-1	-3	2	-0.67	2.52
	Do you feel that any parts of the SCBA are discomfort?		1	1	2	-1	0.75	1.26	1	2	-2	0.33	2.08

Note. For means, -3 = Strongly disagree; -2 = Disagree; -1 = Somewhat disagree; 0 = Neutral; 1 = Somewhat agree; 2 = Agree, 3 = Strongly agree

fit of the SCBA harness around the waist and poor compatibility between the helmet and air cylinder; two female participants reported that the fire helmet easily hit the top of the air cylinder and that the incompatibility restricted their neck movement (Table 7).

Table 7 also shows that, regarding the shoulder strap design, the participants were generally satisfied, with all the male participants and three out of four female participants agreeing that they could adjust the shoulder straps to fit their body. In addition, all the male participants were satisfied with the design and length of the SCBA backplate, while only half of the female participants were satisfied with the design and length. Regarding the waist belt design, the participants' responses were inconsistent; the participants who gave negative feedback indicated the difficulties of tightening the waist belt and adjusting the belt with gloved hands. Regarding the fit of the waist belt, as shown in Table 3, all the participants with a height under 170 cm reported that adjusting waist belt was difficult when it came to fitting it to their waist and pelvis, and they reported uncomfortable looseness with the SCBA. Three out of seven male and female participants reported that they required the additional fit-adjustable design of the SCBA on the backplate length or for the easier use of the waist belt (Table 7). Although the participants showed a positive (satisfied) attitude toward the fit issues of a conventional SCBA harness, the participants showed a negative (unsatisfied) attitude toward the SCBA's wearing comfort. In particular, the participants with a body height under 185 cm reported that their neck extension could be limited because of the poor compatibility of the SCBA and fire helmet. Five out of the seven participants reported that they felt somewhat discomfort when they wore an SCBA.

Pockets

Six out of seven participants had no discomfort with the placement and use of the pockets on the turnout ensemble, as shown in Table 8. Although all male and two out of four female participants were satisfied with the storage capacity of the pockets—with all their heights being over 160 cm—the other two female participants (height less than 160 cm) reported a lack of storage space; they stated that the coat pockets were not used effectively because the SCBA straps prevented access to the pockets and pants pockets because the long coat length covered the pants (Table 8). Furthermore, all the participants agreed that the SCBA harness blocked the opening of the pockets for the turnout coat (Table 8).

Online Survey with 93 Firefighters

On average, the male participants who participated in the online survey were 13.32 cm taller and 18.58 kg heavier than the female participants. Overall, the participants showed statistically significant differences by gender group (male and female) on the 17 of 18 questions that asked about the design issues in the current sizing system, fit, and wearing comfort of the SCBA harness.

SCBA

The female participants had a relatively unfavorable rating of satisfaction when it came to the current fitting system, while the male participants had somewhat positive opinions, as shown in Figure 16. The female participants showed lower satisfaction than males in the questions, stating that the fitting system of the SCBA harness did not well consider the differences of body dimension by individual and by gender: female participants rated the consideration of individual body difference

Table 8

Means and Standard Deviations of Ratings of Evaluation of Conventional Turout Ensemble Pocket Design

Design issue	height (cm)	Female						Male				
		Under 160		160 ~ 170	Over 170	Mean	SD	170 ~ 180	Over 180		Mean	SD
		152	157	165	175			175	180	185		
Are you satisfied with the placement of the pockets on your turnout coat?		-3	2	2	0	0.25	2.36	2	2	2	2.00	0.00
Are you satisfied with the placement of the pockets on your turnout pants?		-2	2	2	3	1.25	2.22	2	2	2	2.00	0.00
Are you easily able to open the pocket?		-2	2	2	2	1.00	2.00	2	2	1	1.67	0.58
Are you satisfied with the storage capacity of the pocket for your firefighting tools?		-2	-2	2	2	0.00	2.31	1	2	2	1.67	0.58
Do you think the SCBA harness blocks the opening of the pocket?		3	2	2	3	2.50	0.58	1	1	1	1.00	0.00
Are you satisfied with the fixing system for the firefighting tools on the pocket inside?		-2	0	-	1	-0.33	1.53	2	0	-1	0.33	1.53

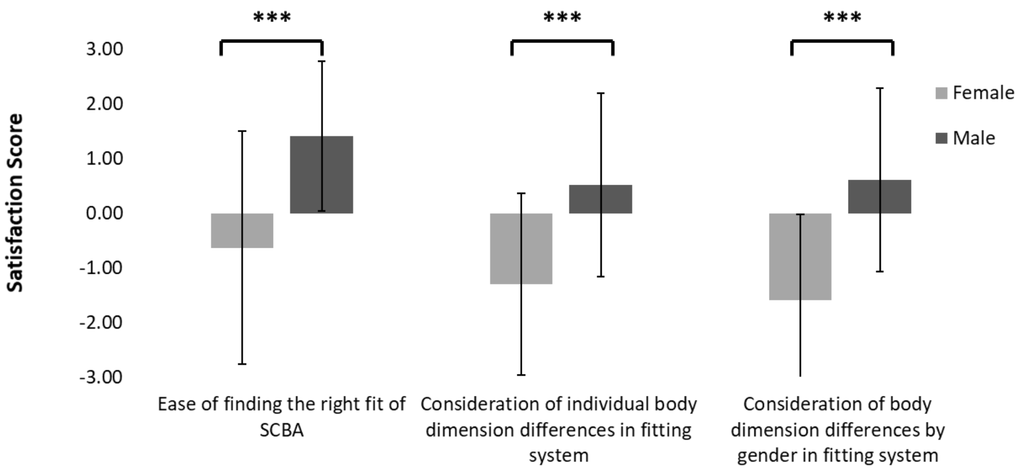
Note. For means, -3 = Strongly disagree; -2 = Disagree; -1 = Somewhat disagree; 0 = Neutral; 1 = Somewhat agree; 2 = Agree, 3 = Strongly agree

as M = -1.30 (± 2.13) and the gender differences as M = -1.59 (± 1.66) for females; for the male participants, they rated each of them as M = 0.52 (± 1.68) and M = 0.61 (± 1.68). However, the female participants thought it was more difficult to find the correct size of the SCBA harness, M = -0.63 (± 2.13), than the males, who thought it was somewhat easy, M = 1.41 (± 1.37), here constituting 2.04 lower points.

As shown in Figure 17, the female participants were unsatisfied with the overall fit of the SCBA harness, reporting M = -1.07 (± 1.84), whereas the male participants were moderately satisfied with the fit, reporting 1.12 (± 1.54). Both the female and male groups responded they could adjust the shoulder strap to fit their body at a moderate level, and the satisfaction with the shoulder strap design was also at a moderate level but 1.73 points higher in males, M = 0.95 (± 1.70), than females, M = -0.78 (± 1.65). Regarding the backplate, the female participants reported moderate opinion on the design of the SCBA backplate but were somewhat unsatisfied with the length of the backplate, with M = -0.93 (±1.90). The male participants were somewhat satisfied with both the design and length of the backplate, M= 1.06 (± 1.48), and M= 1.14 (± 1.53), respectively, while statistically showing a considerable difference in the mean rating of the responses from female participants. Regarding the availability of adjusting the SCBA harness to fit the torso length, the female participants reported 2.11 points more negative feedback, M = -1.67 (± 0.44), here referring to somewhat dissatisfaction than males, M = 0.11 (± 1.12), who had a moderate opinion. The participants had moderate or moderately positive feedback about the fit of the SCBA on waist circumference, with M = 0.11 (± 1.89) for the female group and M = 1.12 (± 1.51) for the male group. The female and male groups also showed moderate or moderate positive opinions of the design

Figure 16

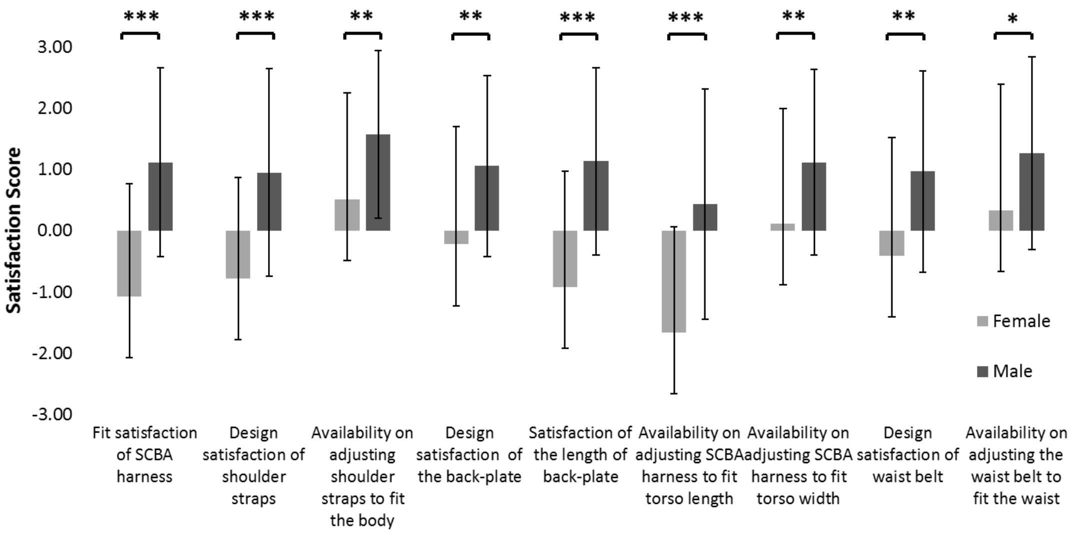
The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of the Conventional SCBA Sizing System



Note. N = 93
*p < .05. **p < .01. ***p < .001

Figure 17

The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of the Conventional SCBA Design and Fit



Note. N = 93
*p < .05. **p < .01. ***p < .001

and the fit of the waist belt, constituting M = -0.41 (± 1.93) and M = 0.97 (± 1.65) in satisfaction with the design and M = 0.33 (± 2.06) and M = 1.27 (± 1.57) in availability regarding adjusting the waist belt to fit the waist or pelvis, respectively. In this survey, only 18.52% of the female participants and 6.06% of the male participants reported that the SCBA harness included the chest strap. Of the participants who said they had a chest strap, women had a tendency to give negative feedback on the design and fit of the strap, while men had neutral feedback, as shown in Table 9.

Table 9

The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of the Conventional SCBA Chest Strap

Design issues of SCBA chest strap		Mean		Standard deviation	
		Female	Male	Female	Male
Your current SCBA has the chest strap?	Yes (%)	18.52	6.06	-	-
	No (%)	51.82	92.42	-	-
	Not mentioned (%)	29.63	1.52	-	-
If your SCBA has the chest strap,	Satisfaction of the chest strap design	-1.50	0.33	2.38	2.89
	Fit-adjustability of chest strap to fit chest	-1.00	0.67	2.45	2.31

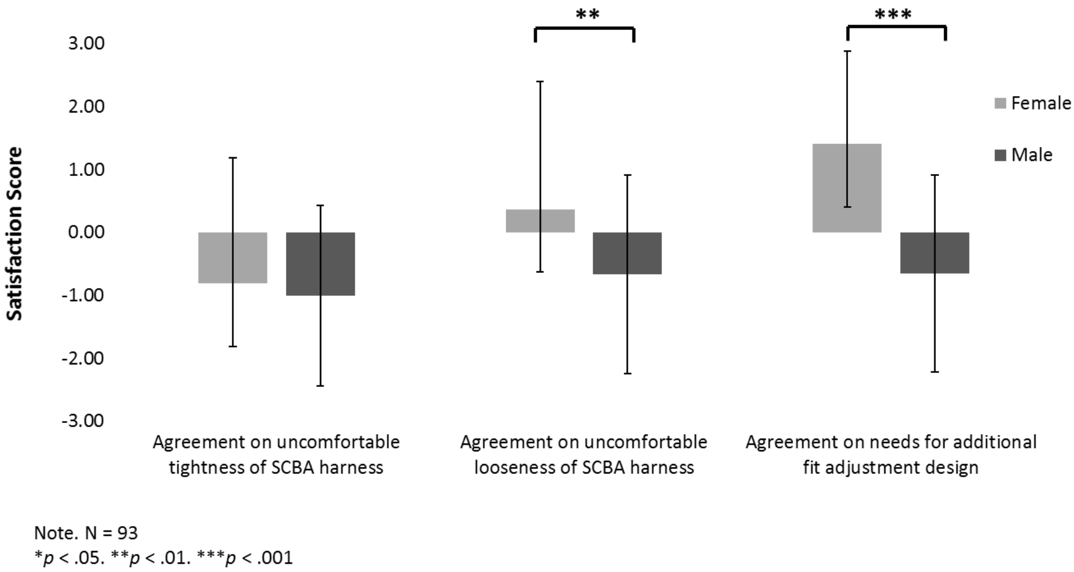
Note. N = 93

Regarding the design and fit adjustability of the SCBA chest strap, the female participants showed somewhat dissatisfaction, rating M = -1.50 (± 2.38) in design and M = - 1.00 (± 2.45) in fit adjustment, and the male participants were more neutral, rating M = 0.33 (± 2.89) and M = 0.67 (± 2.31), respectively.

As shown in Figure 18, regarding the feedback asking about what uncomfortable tight pressure from SCBA to the body, the female and male participants tended to moderately disagree with the type of uncomfortable pressure, M = -0.81 (± 2.00) and M = -1.00 (± 1.44). When it comes to agreement on the uncomfortable looseness of the SCBA, the female and male participants did not show any certain tendency, with M = 0.37 (± 2.02) and M = -0.67 (± 1.57), respectively. The female participants who complained about the looseness of the SCBA harness reported that the ill-fitting issues usually would come from the shoulder and waist straps, fundamentally arising from backplate length. Participants stated the following: *"Shoulder straps can be too loose sometimes based on the backplate length and my torso length," "Shoulder straps are wide and waist belt does not sit on hips," "It's so long, that when I tighten the straps I cannot move my head up or down because my helmet hits the cylinder,"* and *"The shoulder straps tend to be loose enough to slide off my shoulders, even after I adjust them."* In addition, the female participants somewhat wanted an additional size-adjustable mechanism on the SCBA, M = 1.41 (± 1.47), whereas the men reported moderate opinions, M = -0.65 (± 1.56). Most suggestions from the female participants who wanted the additional mechanism were about the length of the backplate and the relation between neck movement and air cylinder: *"Width between the shoulder straps and distance between waist and shoulders is a problem. If I pull the shoulder straps tight to adjust the height of the waist strap, the bottle is too close to my head and I have a hard time looking up. If I leave the straps loose, the waistband is too low on my body," "SCBA length to adjust for short torsos," "Backplate length and where pack sits on his for women is not the same for men. It sits higher on women causing the pack to jam up into helmet when trying to look up at all,"* and *"Maybe*

Figure 18

The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of Conventional SCBA Fit and Need for Additional Fit Adjustment

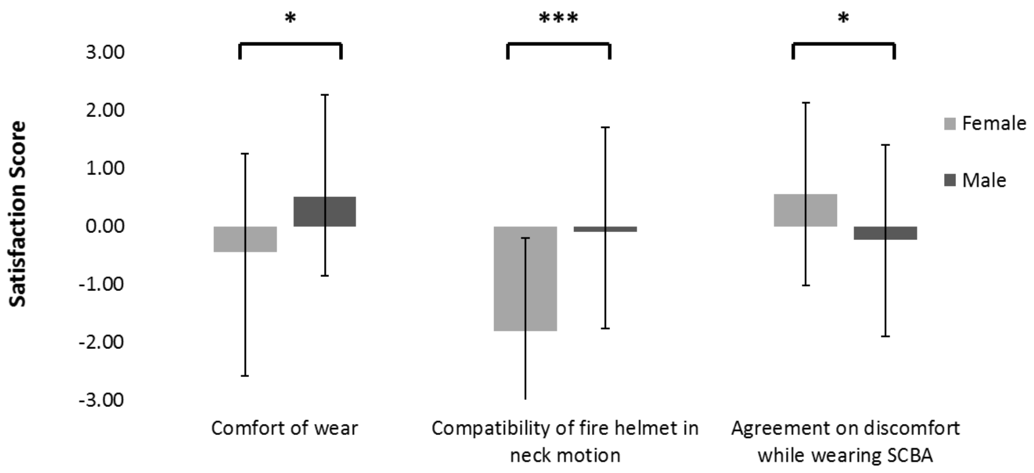


for backplate and the position of shoulder straps with radio spot on gear." The male participants who gave feedback on the size-adjustable designs also commented about the need of adding adjustability to the backplate: *"Backplate adjustment would help dramatically, and a better torso adjustment to keep weight off the shoulders"* and *"Backplate should be able to be lowered to account for curvature in the lower back area."*

As shown in Figure 19, regarding the wearing comfort of the SCBA, both the female and male groups showed neutral satisfaction, M = -0.44 (± 1.69) and M = 0.52 (± 1.75). However, the female participants, M = -1.81 (± 1.62), felt 1.72 points more uncomfortable than the male participants, M = -0.09 (± 1.80), which is at a moderate level, when the female participants bent their neck backward because of the conflict from the wide helmet brim and higher placement of the air cylinders.

Figure 19

The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of a Conventional SCBA's Wearing Comfort



Note. N = 93
*p < .05. **p < .01. ***p < .001

Correlation with Firefighters' Satisfaction with SCBA Design and Height

The Pearson correlation coefficient was measured to determine whether gender was the only factor affecting satisfaction in the use of a conventional SCBA design or if the participants' height would also be a factor. If a coefficient is closer than +1, this indicates that taller participants tended to be satisfied with a conventional design. As shown in Table 10, the questions asking for satisfaction in finding the correct fit of an SCBA harness and whether the current sizing system worked well when considering gender-based body differences had moderate positive correlations between satisfaction and height, with the coefficients, r = .51 and r =.47, respectively.

The questions asking whether the sizing system was well representing the body difference by individual showed a low correlation coefficient (r = .39). Satisfaction with the SCBA harness' general fit shows a moderate positive trend

Table 10

Pearson Correlation Analysis between the U.S. Firefighters' Height and Satisfaction in a Conventional SCBA Design

Question		r
Sizing System	Ease of finding the right fit of SCBA	0.51***
	Consideration of individual body dimension differences in fitting system	0.39***
	Consideration of body dimension differences by gender in fitting system	0.47***
Fit	Fit satisfaction of SCBA harness	0.45***
	Design satisfaction of shoulder straps	0.39***
	Availability on adjusting shoulder straps to fit the body	0.38***
	Design satisfaction of the backplate	0.28**
	Satisfaction of the length of backplate	0.39***
	Availability on adjusting SCBA harness to fit torso length	0.34**
	Availability on adjusting SCBA harness to fit torso width	0.16
	Design satisfaction of waist belt	0.22*
	Availability on adjusting the waist belt to fit the waist	0.26*
	Agreement on uncomfortable tightness of SCBA harness	-0.07
	Agreement on uncomfortable looseness of the SCBA harness	-0.28**
	Agreement on needs for additional fit adjustment design	-0.44***
Wearing Comfort	Comfort of wear	0.30**
	Compatibility of fire helmet in neck motion	0.44***
	Agreement on discomfort while wearing SCBA	-0.30**
Pockets	Placement of the turnout coat pockets	0.30**
	Placement of the turnout pants pockets	0.20
	Ease of accessing to the pockets	0.30**
	Storage capacity for fire tools	-0.05
	Compatibility of SCBA harness in use of pockets	0.15
	Fixing system inside the pockets for fire tools	-0.05

Note: N = 93

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$

Strength of the positive and negative correlation was evaluated using the Evans (1996) guidelines: a) very weak: 0.00-0.019, b) weak: 0.20-0.39, c) moderate: 0.40-0.59, d) strong: 0.60-0.79, e) very strong: 0.80-1.0.

because the height of the participants was higher (r = .45). The satisfaction and height showed weak positive correlation coefficients on the questions asking about satisfaction with the design and ability to adjust the length of the shoulder straps and backplate. The results also indicated their satisfaction with the waist belt design and adjusting the fit, here with weak positive height correlation coefficients ($r = .22$ and $r = .26$, respectively). Because the participants' heights tended to be shorter, they appeared to feel uncomfortable looseness when wearing SCBA harnesses, here with a weak correlation ($r = -.28$). Not only that, because the participants' heights were shorter, they also tended to require additional fit-adjusting designs for their SCBA harnesses. Based on the SCBA's wearing comfort, a decrease in the participants' body height was associated with a decrease in discomfort in wearing an SCBA to a weak degree, and height had a negative correlation with compatibility issues when it came to the fire helmet. Regarding the issues of pocket design and placement, the taller participants showed more satisfaction in the placement of pockets on their turnout ensembles, and the height showed a weak correlation in assessing the pockets ($r = .30$).

4. 1. 1. 2 Review of Fire Helmet Design

Paper Survey

Overall, the male participants showed more satisfaction regarding the design and fit issues of the fire helmet when compared with the female participants, and the female participants took diverse stances compared with the male participants. As shown in Table 11, all the male and two out of the four female participants answered that they could find the correct size of the fire helmet to fit their heads. All the male participants and only one of the four

Table 11

Means and Standard Deviations of Ratings of Evaluation of Conventional Fire Helmet Design

Design issue		height (cm)	Female						Male				
			Under 160		160 ~ 170	Over 170	Mean	SD	170 ~ 180	Over 180		Mean	SD
			152	157	165	175			175	180	185		
Sizing system	Can you easily find the right size of firefighting helmet?		-3	2	-2	1	-0.50	2.38	1	2	2	1.67	0.58
	The size chart is well-considering individual's anthropometrical differences?		-3	2	0	-1	-0.50	2.08	1	2	0	1.00	1.00
	The size chart is well-considering the anthropometrical differences by gender?		-3	2	0	0	-0.25	2.06	2	1	0	1.00	1.00
Fit	Are you satisfied with the fit of your current helmet?		-3	2	-2	-1	-1.00	2.16	2	2	2	2.00	0.00
	Are you satisfied with the headband design of your helmet?		0	2	-2	2	0.50	1.91	2	2	3	2.33	0.58
	Are you able to adjust the headband of the helmet to fit your head circumference?		1	2	-2	1	0.50	1.73	2	2	3	2.33	0.58
	Are you satisfied with the hammock design of your helmet?		0	2	2	1	1.25	0.96	2	2	3	2.33	0.58
	Are you able to adjust the hammock of the helmet to fit your head shape?		-1	1	0	-1	-0.25	0.96	2	2	1	1.67	0.58
	Are you satisfied with the chin strap design of your helmet?		-1	2	-1	-1	-0.25	1.50	1	-1	2	0.67	1.53
	Are you able to adjust the chin strap of the helmet to fit your head and face?		1	2	2	2	1.75	0.50	2	1	1	1.33	0.58
	Do you feel that any parts of the helmet are tight?		-3	-2	-1	-1	-1.75	0.96	-2	-2	-2	-2.00	0.00
	Do you feel that any parts of the helmet are loose?		3	-2	-1	-1	-0.25	2.22	-2	-2	-2	-2.00	0.00
	Do you think you need additional size adjustment mechanism for firefighting helmet?		3	-2	2	-1	0.50	2.38	-2	0	-2	-1.33	1.15
Wear Comfort	When you wear your firefighting helmet, the fit is comfortable.		-3	2	-2	1	-0.50	2.38	1	2	2	1.67	0.58
	Do you feel that any parts of the helmet are discomfort?		0	-2	2	-1	-0.25	1.71	1	-1	1	0.33	1.15
	The helmet can be stably fixed on your head while doing neck motion.		-3	2	-2	1	-0.50	2.38	-1	-2	1	-0.67	1.53
	The helmet works well with the firefighter face mask?		-3	2	2	-1	0.00	2.45	2	2	2	2.00	0.00

Note. For means, -3 = Strongly disagree; -2 = Disagree; -1 = Somewhat disagree; 0 = Neutral; 1 = Somewhat agree; 2 = Agree, 3 = Strongly agree

female participants agreed that the fire helmet sizing system took into account variations in head sizes by individuals and gender groups. Regarding the fit and design elements of the current fire helmet, in general, all the male participants showed satisfaction for 9 out of 11 questions, while all the female participants showed their satisfaction for only two (Table 11). Three out of the four female firefighters complained of the poor fit of the fire helmet, whereas all the males were satisfied with the fit. Specifically, only one female participant showed dissatisfaction with the design and fit of the headband of the fire helmet, and the others were slightly satisfied or had neutral opinions. Regarding the hammock of the helmet, three out of the four female participants demonstrated their satisfaction with the design, but three out of the four showed dissatisfaction with the hammock fit. Regarding the design of the chin strap, the opinion of the participants was various, but all the male and female participants agreed that they could adjust the chin strap to suit their heads. All the male and female participants did not show discomfort from the tightness of helmet fit, and only one female participant of whole participants showed discomfort from the looseness of the fit. The individual's wearing comfort of the fire helmet was different; all male and half of the female participants were satisfied with the wearing comfort of the helmet (Table 11). However, two out of three males and half of the female participants reported that the helmet was not stably placed on their head after neck or head movements.

Online Survey with 93 Firefighters

Fire Helmet

In general, to find the right size of helmet, each of the female and male participants showed moderate and somewhat positive opinions, M = - 0.37 (± 1.90) in the female group and M = 1.44 (± 1.28) in the male group, as shown in Figure 20. Regarding the questions asking if the sizing system was well considering the differences by individual and gender, and female and male participants reported moderate feedback on average.

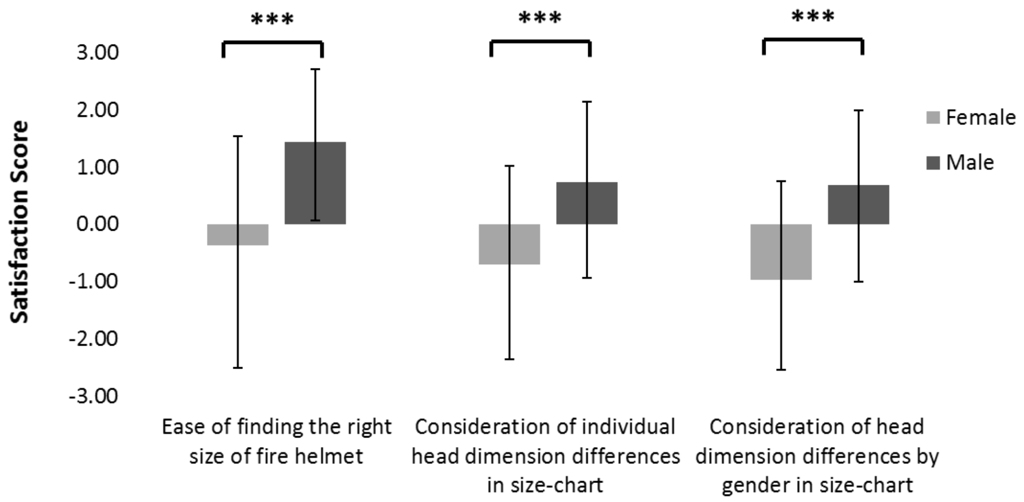
Regarding the overall fit of the fire helmet, as shown in Figure 21, the female participants tended to have a moderate level, M = -0.59 (± 1.87), whereas the male participants were somewhat satisfied, M = 1.24 (± 1.49). In addition, the female group reported moderate feedback regarding the designs and fit-adjustability of the headband and hammock, and the male group reported somewhat satisfied feedback regarding the designs and fit-adjustability of the headband and hammock. Both groups were somewhat satisfied with the design (female: M = 1.00 (± 1.59), male: M = 1.15 (± 1.48)) and fit-adjustability (female: M = 1.37 (± 1.39), male: M = 1.71 (± 1.02)) of the chin strap. Besides, although all the participants did not illustrate any strong discomfort from a tight or loose fit from the helmet, the female participants somewhat agreed with the need to add more size adjustment mechanism for the helmet, M = 1.11 (± 1.91), while the male participants had a moderate opinion, M = -0.79 (± 1.53) (Figure 22). Regarding the wearing comfort of the helmet, as shown in Figure 23, both groups generally took neutral stances, but the female group complained about the unstable wear of the helmet.

Correlation of Firefighters' Satisfaction with Fire Helmet Design and Height

The Pearson correlation coefficient was measured to determine whether gender was the only factor affecting satisfaction in the use of a conventional fire helmet design or if the participants' heights would also be a factor affecting satisfaction. As shown in Table 12, for the questions on the satisfaction of finding

Figure 20

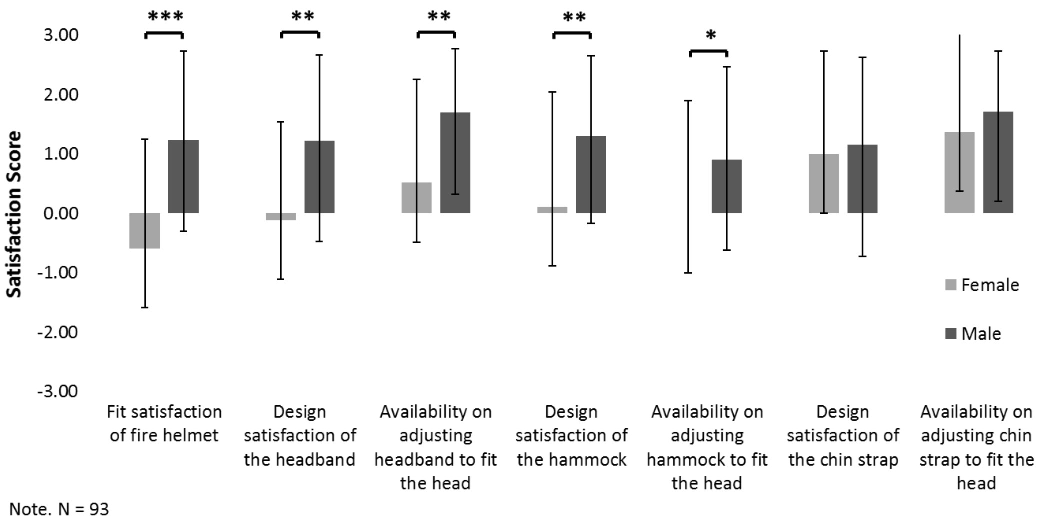
The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of the Conventional Fire Helmet Sizing System



Note. N = 93
*p < .05. **p < .01. ***p < .001

Figure 21

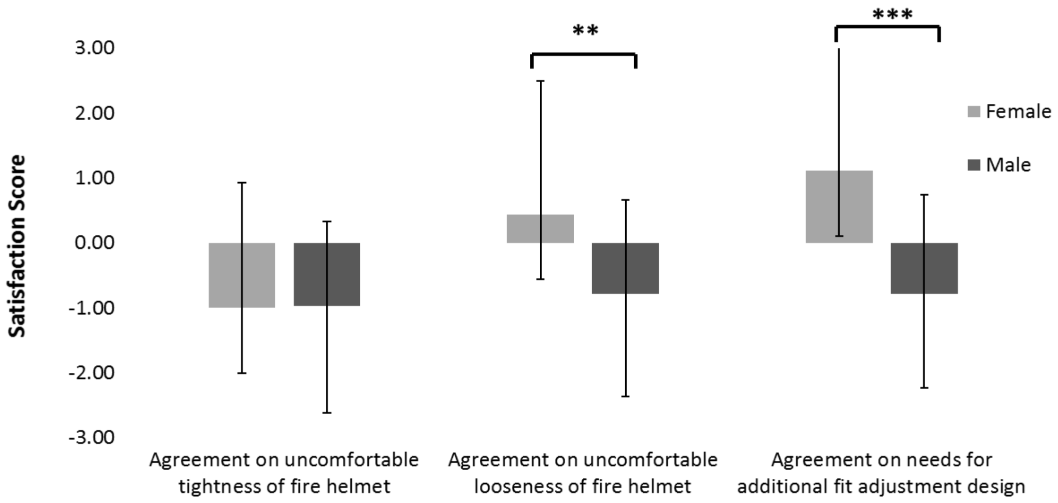
The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of the Conventional Fire Helmet Design and Fit



Note. N = 93
*p < .05. **p < .01. ***p < .001

Figure 22

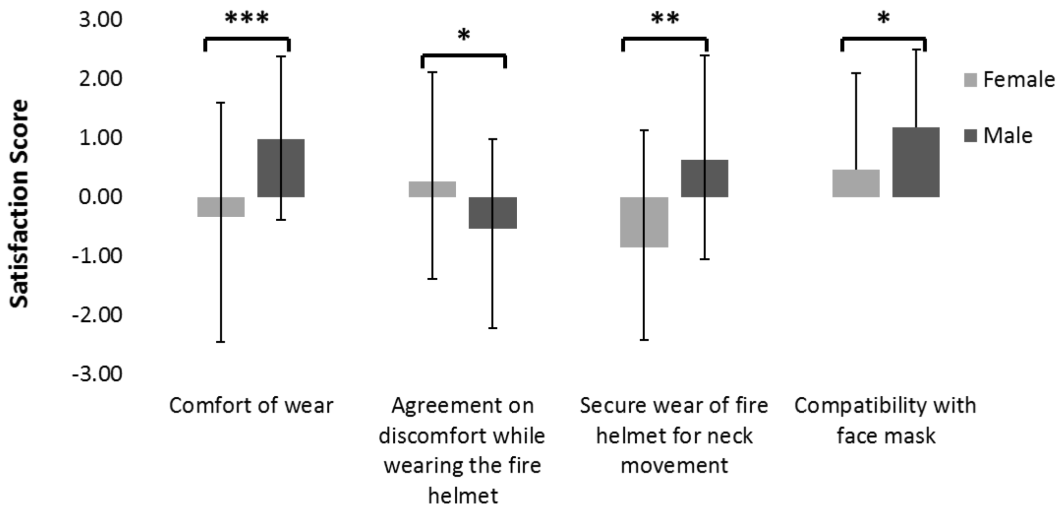
The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of the Conventional Fire Helmet Fit and Need for Additional Fit Adjustment



Note. N = 93
*p < .05. **p < .01. ***p < .001

Figure 23

The Means and Standard Deviations of the U.S. Firefighters' Ratings of Evaluation of the Conventional Fire Helmet Wearing Comfort



Note. N = 93
*p < .05. **p < .01. ***p < .001

the correct fit of the fire helmet and whether the sizing system well reflected the individual body differences, the responses had weak positive correlations between satisfaction and height, with r = .37 and r = .31, respectively. Regarding the question of asking whether the sizing system reflected the body difference by gender, satisfaction showed a moderate positive correlation coefficient (r = .42) with height.

Satisfaction in SCBA harness' general fit showed a weak positive correlation because the height of the participants was higher (r = .34). Regarding the questions asking satisfaction about the design and fit adjustment of the fire helmet's headband and hammock, the participants' satisfaction showed weak positive

Table 12

Pearson Correlation Analysis between U.S. Firefighters' Height and Satisfaction in the Conventional Fire Helmet Design

Question		r
Sizing System	Ease of finding the right size of fire helmet	0.37***
	Consideration of individual head dimension differences in size chart	0.31**
	Consideration of head dimension differences by gender in size chart	0.42***
Fit	Fit satisfaction of fire helmet	0.34**
	Design satisfaction of the headband	0.33**
	Availability on adjusting headband to fit the head	0.31**
	Design satisfaction of the hammock	0.24*
	Availability on adjusting hammock to fit the head	0.26*
	Design satisfaction of the chin strap	0.04
	Availability on adjusting chin strap to fit the head	0.21*
	Agreement on uncomfortable tightness of fire helmet	0.07
	Agreement on uncomfortable looseness of fire helmet	-0.23*
	Agreement on needs for additional fit adjustment design	-0.31**
Wearing Comfort	Comfort of wear	0.17
	Agreement on discomfort while wearing the fire helmet	-0.05
	Secure wear of fire helmet for neck movement	0.28**
	Compatibility with face mask	0.21*

Note: N = 93

**p* < .05. ***p* < .01. ****p* < .001

Strength of the positive and negative correlation was evaluated using the Evans (1996) guidelines: a) very weak: 0.00-0.019, b) weak: 0.20-0.39, c) moderate: 0.40-0.59, d) strong: 0.60-0.79, e) very strong: 0.80-1.0.

correlation coefficients with height and regarding the length adjustment of the chin strap; satisfaction had a weak positive correlation with height. Because the height of the participants was shorter, they tended to experience uncomfortable looseness when wearing a fire helmet, here with a weak correlation (r = -.23); they also required additional fit-adjusting designs on the fire helmet (r = -.23). The height also showed weak correlation coefficients with satisfaction in the secure wear (r = .28) of the helmet and the compatibility of the helmet facial mask (r = .21).

4. 1. 2 Empirical Suggestion for Improving Firefighters' PPE Design

4. 1. 2. 1 Suggestion for SCBA Design

Dislikes of the SCBA Harness Design

When participants were asked about the areas of complaints of their SCBA harness, four participants pointed out the looseness, twists, or uneasy access of straps. Among them, the shortest female participants, whose height is 152 cm, reported more complaints than others, which might be unfavorable to shorter firefighters. Firstly, she indicated the looseness of the waist belt, that *"Even if I'm in the waist belt, it doesn't cinch down nearly as tightly as it should. I mean like I'm obviously like there are girls that are tiny little waist and they can't. They have their waistband all the way as far as it'll go and it's still loose on them (Participant #3)."* Secondly, she stated the unstable condition of the shoulder straps; *"The shoulder straps are constantly coming undone. Whenever I'm doing any work, the shoulder strap especially the left one. It's always the left one for some reason and I don't know why but it's always coming loose. So, it's sliding on my back as I'm wandering around which is really annoying (Participant #3)."* Lastly, twisted shoulder straps were pointed out; *"The shoulder straps are always getting twisted and daring. They twist* *and I don't know how it happens because and it's happened with me even when I've gone in and adjusted my air pack. When I'm coming on duty, I always check my SCBA straps and, 80 percent of the time, they're always twisted somehow ...And so you can't cinch down because now it's stuck and so that's a huge issue. It's an annoyance for sure, but it's also a safety issue because if I need to take that pack off for some reason to do an escape or something, I might not be able to do it because my strap is twisted. So now I can't loosen the straps to pull the pack off to do an escape maneuver because my straps are twisted (Participant #3)".*

Fit

In terms of the fit-adjustable design of SCBA, two female participants reported that the current SCBA body is not suitable for the torso of the short or slim firefighters and the other five participants complained about the current fit-adjustable design features (shoulder and waist straps). The two female participants who complained about SCBA's body had a relatively short body height of less than 160 cm and replied that the SCBA backplate is either too wide or too small. A female participant suggested a length-adjustable SCBA body, but also stated the expected adverse effects of the length-adjustable design, such as increased donning and doffing time for adjusting; *"I mean an adjustable backplate would be super nice because it helps accommodate your torso. I guess the negative thing though is you're going to hear your co-workers complaining like you left the SCBA in the shortest setting and didn't return it to normal, but it'll be okay and it'll be fine, I don't see any issue with that (Participant #3)".*

The participants who complained about the current fit-adjustable design reported finding the shoulder and waist straps or changing the straps is difficult. One participant who mentioned difficulties in finding straps due to the wearing thick fire gloves stated that *"The straps sometimes hard to find when you wear your gloves like when you're adjusting or you're putting on the waist strap (Participant #4)"*. Three out of seven participants suggested shortening the straps or adding bigger rings as the solution making it easier to find straps. Several participants who described the difficulties in strap adjustment mentioned that the straps appear to be twisted making it difficult to tighten and loosen the straps; *"Sometimes the shoulder straps are twisted and even on the waist, this thing gets flipped out. When you move around, the buckles are also moving. It's nice to be tightened smoothly, but sometimes it works really hard. A lot of moving is around and straps are stuck to be tangled among themselves (Participant #7)."* In addition, the participants mentioned that the straps tend to be loosened during wearing the straps, which also makes it difficult to adjust the straps; *"I can never get tight enough the waist belt. Yeah, cause you can never tighten it enough hold on for a long time. It's getting loose so normally I do unclip it first and have to tighten and then clip it (Participant #2)."*

Closure System

The participants were generally satisfied with SCBA harness's current donning and doffing system. Two participants reported, however, that larger belt clips or adding rings at the edge of the waist strap could help make it easier to grab the straps with fire gloves to don and doff. For SCBA's closure system participants appeared to prefer seatbelt type and larger waist belt clip for better use with fire gloves; *"It has a seat belt style, released in the middle and that's ok. It's again it's not quite large enough for gloved fingers. I think if they just get standardized like seat belt closure and use that and you can usually find that, something it is easier to find (Participant #6)."*

As an element of design the participants like to customize or add, three participants mentioned the easier use of waist buckle; *"I would like to be able to have some sort of quick release system ...but it's not like glove-friendly (Participant #3)."* and *"Easier unclip of waist buckle, my one is slippery so hard to unclip on it (Participant #4).", "The waist belt easier to tighten will be great (Participant #2)."*

Weight Distribution

Regarding carrying the weight of SCBA, two out of four female participants indicated that most of the SCBA's weight was on the shoulder rather than on the pelvis; *"I've definitely wanted to have it mostly not on my shoulders. I get tired a lot faster on that. It is kind of hard to adjust your shoulder strap or your waist strap tight enough that you can feel comfortable like putting weight on your pelvis and that's usually my concern (Participant #1)."* Male participants did not have any complaints about current weight carrying style and weight pressure in general, but they reported that the waist belt is easily loosened, which impedes an efficient weight distribution on the pelvis. Although the participants agreed that the SCBA waist belt blocks access to the pockets on the turnout coat, they tended to be satisfied with the current pocket design because they do not use the pockets that much but only for gloves and eye goggles.

About half of the male and female participants (three of seven) indicated that SCBA's heavyweight or uneven weight distribution causes job errors and backpains while working on the fireground with SCBA; *"It Pretty much pushes your entire center of mass backward. when you're standing up it isn't a big issue but, if you're going down into it, it can be kind of disorienting (Participant #1).", "If it was just a lower profile and it is heavy, I mean they are not wrong when they say it's heavy. The thing it's super heavy with huge back pains. They're heavier than they* *were because they have just so many new gizmos now. They're heavy. So, I think it's especially really really important that it's properly distributed in size because they are heavy (Participant #3).",* and *"Your balance can be thrown off. You don't have it tightened downright (Participant #7)."*

As solutions to reduce such work errors, the suggestion of the participants involved a more effective weight distribution, such as adding a chest strap for the secure wearing of shoulder straps, color coding on shoulder straps for even weight distribution, adopting a body-contoured backplate design, putting more weight on the pelvis than the shoulders; *"Chest strap helps a lot for me for distributing weight (Participant #2)."*

"There is a like a way to tell when the straps are even. So they're like color coding, maybe on the straps to say like, okay, this strap is tightened down to the green or this one is tightened down to the orange. That will be hard to maintain but they will give you a sense of how tight they are because sometimes working at them they look like the different lengths, but the color on the colored bands shows how you tightened this much, you tightened this much ... Sometimes that can be hard to tell but you can even make it as reflective one too (Participant #7)."

"The backplate is a little big sometimes, it's flat and not contoured to that. It's not very adjustable for that and it can be uncomfortable sometimes. (Participant #4).", and *"Weight is still focused and it is on your shoulders, not much on your waist strap. I think it should be like 90 percent the weight should be on waist strap (Participant #5)."*

The other suggestion for reducing the errors included easier use of SCBA with fire gloves by adopting bigger, thicker, and rounder rings on the straps;

"everything about it should be made to use with gloves. So like the rings should be bigger and thicker and rounder. (Participant #6)."

Placement of Backplate and Waist Belt

Four out of seven participants agreed that their neck movement is limited because the back brim of the helmet hits the upper part of the air cylinder; *"I have a metro style helmet. I'm always when I go up and I look up, the back of my helmet is always hitting the cylinder in the back, so I can't look all the way up. ...For example, if I were to put up that ladder or whatever, I'm trying to look up to see how high I need to raise it, I can't do that. (Participant #3)."*, *"When I wear a helmet like the black one or really classical design one, I can't ever fully tilt my head back because it's going to hit my back. Especially with the traditional helmets, it's hard to tilt my head backward (Participant #2)."*, and *"I've got one of the ten ten styles that the duck builds too long in the back. So if I turn my head too far back like this, it hits so I have a limitation of being on the move (Participant #6)."*

A participant wanted to customize the backplate positioning; *"Just a way to somehow adjust and distribute it would be super helpful. I would just really like a lower profile SCBA bottle. You know, I mean who's to say that the cylinder needs to be placed up or down and why can't it be placed sideways (Participant #3)."*

Stability of Wearing SCBA

When it comes to the stability of SCBA on the body, the unstable ratchet strap was pointed out; *"Sometimes the bottle, it's not secure. I like that the actual hardness is secure but the bottle in the pack is actually kind of not (Participant #1)."* and *"There's one thing that goes wrong sometimes which is that the strap itself like a cylinder because this is a metal band. If a lot of times is hard to tighten just right which means that even though the cylinder is attached to the bottom part and* *perfectly secure and it's clipped in, it's not going where but it's still sort of like it can move like a fraction of an inch because it's like the clink you're moving back and forth. It's not going to fall off. It's just annoying. I like that's a good lean forward to get a little smack on the back and if you lean back. So, it's just really it's really really hard to tighten those or loosen them depending on how it is (Participant #6)."* A participant indicated instability of shoulder straps as well as ratchet strap; *"Sometimes those ratchet straps can like come loose like flopping around. Sometimes your shoulder strap comes loose so the SCBA is kind of like moving around and then you try to like yank it so you can cinch it down, but then the straps will get twisted, so it's not as tight as you want it (Participant #3)."*

4. 1. 2. 2 Suggestion for Fire Helmet Design.

Need for improvement in Fire Helmet Design

Two participants reported that the visor is their dislike part of the fire helmet because the visor easily slips down; *"My eye protection tends to slip down (Participant #4)."* and *"The flipped down visors that we have and they are nice and the ones that do like the two-piece flipped down like those ones but a lot of times they're too small. If you're wearing glasses underneath, especially when you like wider glasses they're too small to wear over to glasses (Participant #5)."*

Fit

Five out of seven participants reported the poor fit of the fire helmet. They reported the helmet fit they're wearing on their heads a little loose or tight.

"Right now they click and they adjust a certain amount of headband. That can be a smaller amount and more precise the adjustment would be good for me

because I know I like between sizes now so it's either too tight or too loose ...But, I just can't find the comfortable tightness of the headband for me (Participant #2)."

"So my firefighting helmet is always coming loose on my head. So they tell you like what you should do is you should put it on your head and well they say you should put your face piece, put your hood on, put it on your head, cinch it down, and then take everything off, and then talk your …what's the word I'm looking for is adding the little tail liner inside and that should fit your head ...So, for me, the ratcheting mechanism like the headband will still come loose like that thing is always coming off of my head. Like I'll bend down and my helmet will come with me or it will fall off my head and I can cinch down the chin strap, but that only goes so far. And then the other thing that a lot of guys don't really run into is it doesn't accommodate for a ponytail. I have to wear my hair low or like really high because I can't get the helmet on if I have a ponytail on or won't fit right. Let me put it that way. (Participant #3)."

"I always tight on my forehead, but not tight enough on the top of the head on the basket part. Even though do tight, but I still feel like all of these bands (Participant #4).", "The helmets work now is that they have the chin strap that you tighten and then also the thing that you can adjust about your head. And that makes a difference because pointing it on your head has to go over the crown and that's the wide part but then needs to actually tighten below. It is here. So that's a narrower part of your head. So you want to just give it a few cracks (Participant #2).", and *"I have a pretty small head at the top, so my helmet is always loose. Because when I put my hood on my mask. It's got to be a little bit looser. Thus, this is how I wear my helmet (Participant #7)."*

Closure System

Four participants out of seven were satisfied with the current donning and doffing system of the fire helmet. However, two participants reported that sometimes releasing chinstrap is difficult and it will be easier to work with fire gloves to adopt a bigger buckle on the chin strap. Most of the participants had no complaints about current closure system of a fire helmet, but some of the participants really liked using the Postman's slide fastener for donning and doffing by adjusting the length with that fastener and they also had no specific complaints about the current liner design, but two female participants required more ponytail-friendly liner and helmet design. Also, participants have any specific complaints on the current helmet's hanging system and participants tended to agree that the current fire helmet is well designed to work with hood and mask.

Placement of Helmet

Two female participants reported they are in need of more ponytail-friendly helmet positioning as an answer to which helmet design elements would be customized in terms of positioning. To the question asking which helmet elements firefighters would like to remove, two participants replied that the back brim of the fire helmet is so long that the brim easily hits the top of the air cylinder.

Stability of Wearing Helmet

Due to the loose fit of the helmet, three of the four female participants reported that the helmet is not stable on their head; *"Sometimes it slips around a bit if I have a little looser. So, try and put it tighter though I'll get a headache so I'll make it a bit more certain that. Especially, when I'm packing hose and looking down the helmet or slip off of it (Participant #2)", "If I wear it properly yes, but when wearing for a long time it is getting loosen, then I'm retightening the headband*

(Participant #4)." On the other side, most of the male participants did not complain about the fit of helmet excepting one male participant who reported the clumsy fit of the helmet; *"If I wear it properly yes, but it's got a be really tight or it isn't really tight. Everything is not fitting perfectly (Participant #7)."*

Eye Shield

Two participants reported that the visor is their dislike part of the fire helmet because the visor easily slips down; *"My eye protection tends to slip down (Participant #4)."* and *"The flipped down visors that we have and they are nice and the ones that do like the two-piece flipped down like those ones but a lot of times they're too small. If you're wearing glasses underneath, especially when you like wider glasses they're too small to wear over to glasses (Participant #5)."* One participant answered that the eye shield attached to the helmet is not useful.

4. 1. 3 Empirical Review of Prototype 1.

4. 1. 3. 1 SCBA Harness Prototype 1 Review.

Feedback on the Height-Adjustable Waist Belt of SCBA Prototype 1

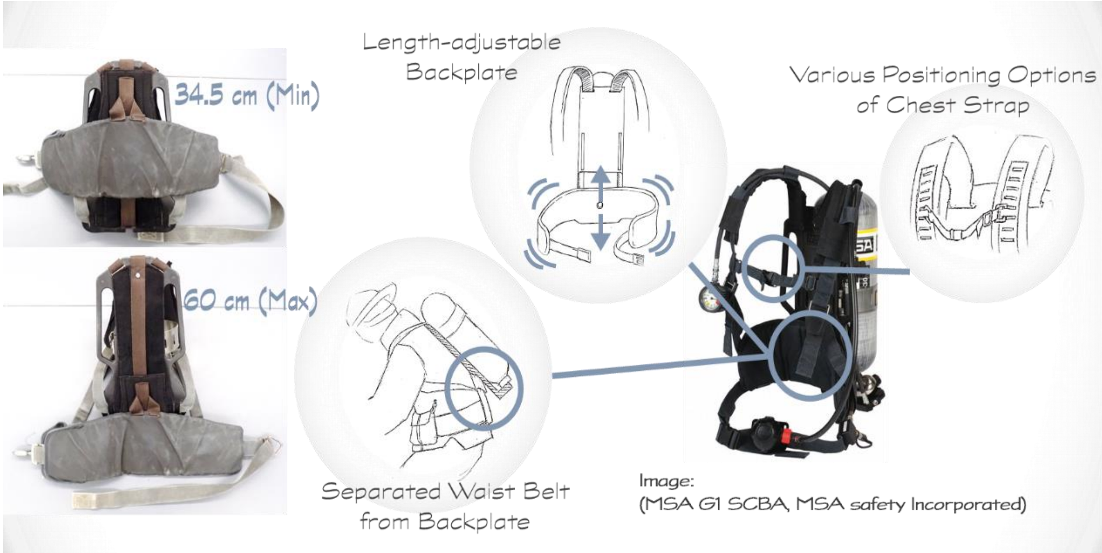
All-female participants (n = 4) responded favorably to the main design feature of the first SCBA prototype (Figure 24): the height-adjustable waist belt. They agreed on the needs of additional fit-adjustable designs for the SCBA harness as well. Although the male participants also thought positively about the idea of adding a height-adjustable device on the waist belt, some reported that they did not feel any need for additional fit-adjustable designs of the harness.

Demand for Faster and Easier Adjustment

Regarding the demand for faster and easier adjustment, the main concern about the first SCBA prototype was how quickly and easily firefighters would

Figure 24

Key Design Points of SCBA Prototype 1



change the height of the waist belt when donning and doffing for a quick response to an emergency call. Most of the participants reported that the procedure for adjustment would add considerable time and effort

when donning and doffing while optimizing the height of the waist belt by using the hook-and-loop fasteners and loosening the belt to the original condition for the next emergency call. To illustrate this, a firefighter said, *"My question is how fast you can adjust the backplate. It may not work if it takes a while to adjust it. You know, no time for spending time for calling to adjust it (Participant #2)."* Another firefighter also mentioned, *"Yes, the one thing is that if you have a small person just before you, it's gonna be a wait to tighten it and then you have to all loosen it, so the time could take differently (Participant #4)."*

A firefighter suggested a solution regarding the height adjustment for quicker and easier donning and doffing: "*Just in general, the problem, adjusting* *takes some time, so maybe if you could move the waist belt up and down by pulling straps. It could be much easier than having a Velcro in (Participant #4)."*

Feedback on the Other Design Features of SCBA Prototype 1

Regarding the other design features on the first SCBA prototype, a female and male participant said that releasing the lower part of the backplate would be beneficial for easier bending back: "*I think the separate waist belt can be useful because, when you wear a board on your back, it could be so far (Participant #4)"* and "*I'll be interested to try with that when it is separated from the backplate. I would like to try that, but I also don't know how it will be comfortable because when it pushed on to my back. It would be sometimes small (Participant #7)"*. Furthermore, a firefighter gave positive feedback on the increased options for placing chest straps: "*I think focusing on the SCBA body will be the best but I like the adjustable chest band you have. It looks pretty good seemed to kinds of great one on considering body proportions* (Participant #5)".

4. 1. 3. 2 Fire Helmet Prototype 1 Review.

Feedback on the Extended Liner of Fire Helmet Prototype 1

The participants were generally satisfied with the fit of the conventional fire helmet or did not require the additional securing designs, and they agreed to the need for a more secure hanging system of the helmet. A male firefighter who had complained about the loose fit of the conventional fire helmet gave positive feedback about the improved fit of the first helmet prototype 1 (Figure 25). This male firefighter reported that adding a liner can better secure the helmet, and the helmet movement seemed to be better matched with head movement. However, he also mentioned that

Figure 25
Fire Helmet Prototype 1 with the Extended Liner

the many straps in the extended liner can make it harder to wear the liner around the ear: *"It's a lot better. It does feel like a lot back here and that might affect how I put my mask on because the mask and hood add quite a bit space, but that feels really much more secure (Participant #7)"*. Additionally, half of the participants commented on a positive effect of the extended liner for a more secure hanging system but also stated another possibility: the liner's many added straps could prevent the helmet from working with the hood and mask.

4.1.4 Summary of the Empirical Reviews for PPE Design Development

This phase mainly examined the design and fit issues identified by feedback from different gender and various height with the self-assessment of the U.S. firefighters. The online survey responses showed that the female participants (n= 27) were less satisfied or more dissatisfied compared with the male participants (n= 66) on 17 out of 18 questions asking about the current sizing system, design, fit, and wearing comfort of the conventional SCBA harness and on 14 out of 17 questions asking about the fire helmet designs. Not only was gender a factor affecting satisfaction in the fit and design of a conventional SCBA harness and fire helmet, but the height of the firefighters was also a factor affecting the satisfaction in the sizing system, design, fit, and wearing comfort. The survey determined that satisfaction of the design and fit of an SCBA harness and fire helmet have somewhat positive correlations with the height of firefighters, meaning that taller firefighters tended to feel greater satisfaction in an SCBA and fire helmet than shorter firefighters. For the questions about the SCBA harness's fit and design, 16 out of 18 questions' results showed weak or moderate positive correlations with height. Regarding the fire helmet's fit and design-related questions, 13 out of 17 questions' results showed weak or moderate positive correlations with height. Additionally, regarding the satisfaction in the use and placement of pockets on the turnout coat and pants, only two out of six questions had weak correlations with height. According to the demographic information of this online survey, on average, the height of the female firefighters was 13.32 cm shorter than the male firefighters.

For the interviews conducted to collect the empirical suggestions for SCBA harness and fire helmet design improvement, the participants pointed out that the easy use of the SCBA harness and fire helmet hanging system with fire gloves would be required, for example, by applying bigger buckles or adding rings on the straps for easier grabbing.

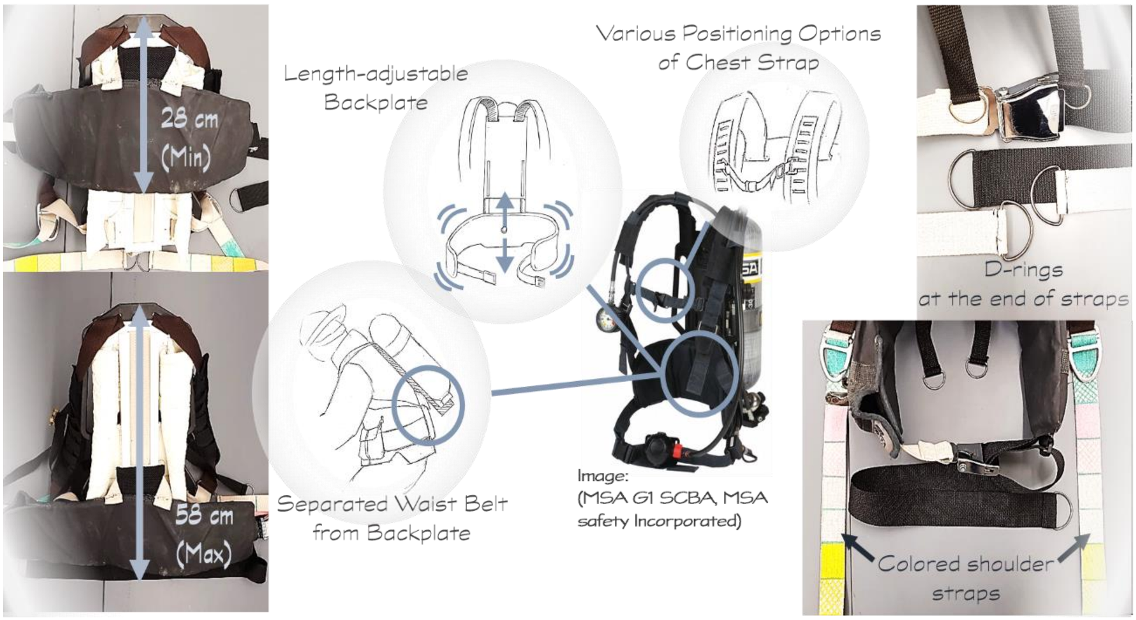
For the review of prototype 1, the participants were satisfied with the added fit-optimizing design of SCBA harness and fire helmet. However, the participants also pointed out the need for easier and quicker length-adjusting methods for the SCBA waist belt and fit-adjusting method for the helmet's extended liner for a quick response to an emergency call.

4. 2 Phase Ⅱ: Design Evaluation of Compatible Firefighters' PPE

The second SCBA prototype has 30 cm in height-adjustable range (min: 28 cm, max: 58 cm) on a backplate (Figure 26), while a conventional backplate design has a fixed length (52 cm). According to Size USA (TCsquare Inc.) data from 3647 of male and 6813 of female in the U.S., the height-adjustable range of this prototype can cover 98.19% of males' and 99.99% of females' back length, while the height-adjustable waist belt would be at the optimal height of each person's waist.

Figure 26

Key Design Points of SCBA Harness Prototype 2 and the Height-adjustable Range of Waist Belt



To evaluate the effects of the prototype 2 designs, a paper survey was conducted to compare participants' subjective feedback on ease of donning and doffing, ease of use, wearing satisfaction, and changes in movement while wearing prototype 2 and conventional designs. To assess prototype 2's effects on the wearers' upper body movement, static ROM collected by 3D body scanning was analyzed. Prior to analyzing the static ROM, a normality test was conducted. Because the significance level is greater than 0.05, the raw data of the static ROM can be concluded to be normally distributed, meaning the data are valid for parametric analysis. Except for lumbopelvic and neck flexions, the significance levels of static ROM motion were greater than 0.05 in seven out of nine motions while the research participants were wearing both the fire helmet and SCBA (Table 13). In the seven static range of motions, a dependent t-test was conducted for analysis, meaning that the results analyzed from the collected data can be reliably elicited through the parametric analysis methods, here the Shapiro-Wilk normality test. To analyze the static ROM of lumbopelvic and neck flexion, a nonparametric analysis—the Wilcoxon signed-rank test—was performed.

Table 13

Shapiro-Wilk normality Test for Verifying Static ROM Data Analysis

Type of Gear	Static ROM	Shapiro-Wilk		
		Statistic	df	Sig.
SCBA	Distance with helmet(mm)	0.916	6	0.478
	Lumbopelvic flexion	0.788	6	0.046
	Lateral flexion	0.967	6	0.87
	Neck extension	0.938	6	0.642
	Neck flexion	0.691	6	0.005
	Lateral neck flexion	0.810	6	0.072
Fire Helmet	Neck flexion	0.909	6	0.432
	Neck extension	0.801	6	0.061
	Lateral neck flexion	0.809	6	0.071

* This is a lower bound of the true significance.

4. 2. 1 Design Evaluation of SCBA Harness Prototype 2

Subjective Feedback of SCBA Prototype 2

A Wilcoxon signed-rank test for SCBA (Table 14) showed that the type of gear did not elicit a statistically significant change from participants when it came to the ease of donning and doffing procedure of the SCBA on the paper survey. The participants' responses also showed no statistically significant differences in satisfaction between the conventional and prototype 2 SCBA in ease of length adjusting and access to the waist belt and shoulder straps. Nonetheless, the participants could more easily assess the degree of the shoulder straps' length change and balance in prototype 2 (M = 2.13) than a conventional SCBA (M = -.12). Regarding the ease of adjusting the height of the waist belt of prototype 2, the participants responded positively (M = 1.38), and in terms of access to the backplate for height-adjustment of the waist belt (M = 0.88) and assessing the height of the belt (M = -.63), they showed almost neutral opinions. Regarding the wearing stability of the SCBA, the participants were more satisfied with prototype 2 (M = 2.25) than the conventional design (M = .63) but did not show statistically significant differences in wearing comfort satisfaction and weight and fit compression from the conventional SCBA. Regarding the self-assessment of body movement, the participants agreed there was less restriction in lumbopelvic flexion while wearing prototype 2 (M = .12) than the conventional SCBA design (M = 1.75) but did not identify statistically significant differences in other body movement and mobility while wearing the different types of SCBA.

Table 14
Wilcoxon Signed-rank Test Comparison Regarding Satisfaction in the Use of SCBA by Type of Gear (Conventional SCBA and Prototype 2)

Question	Type of gear	Mean	SD	Min	Max	Z	Asymp. Sig. (2-tailed)
Donning time (sec)	Conventional	22.83	4.40	17.64	30.91	-2.380b	0.017*
	Prototype 2	30.69	5.62	23.90	38.81		
Doffing time (sec)	Conventional	9.31	2.88	5.50	12.74	-1.859c	0.063
	Prototype 2	7.61	3.60	3.27	13.26		
Ease of donning	Conventional	0.88	1.55	-1	3	-.108c	0.914
	Prototype 2	0.75	1.58	-2	2		
Ease of doffing	Conventional	1.50	1.85	-1	3	-1.089b	0.276
	Prototype 2	1.88	1.36	-1	3		
Ease of access to shoulder straps for length adjustment	Conventional	1.88	0.99	0	3	-1.342c	0.180
	Prototype 2	1.50	1.07	-1	2		
Ease of length-adjusting shoulder straps	Conventional	2.13	0.64	1	3	-.816c	0.414
	Prototype 2	1.75	1.17	-1	3		
Ease of assessment of length adjustment and balance of shoulder straps	Conventional	-0.12	1.64	-3	2	-2.132b	0.033*
	Prototype 2	2.13	1.36	-1	3		
Ease of access to waist belt for length adjustment	Conventional	0.75	1.83	-2	3	-.828b	0.408
	Prototype 2	1.13	1.64	-2	3		
Ease of length-adjusting waist belt	Conventional	0.63	1.51	-2	2	-.954b	0.340
	Prototype 2	1.38	1.30	-1	3		
Ease of assessment of length adjustment of waist belt	Conventional	0.63	2.00	-2	3	-1.289b	0.197
	Prototype 2	1.50	1.51	-2	3		
Ease of access to backplate for height adjustment of waist belt	Conventional	-	-	-	-	-	-
	Prototype 2	0.88	1.81	-	-		
Ease of height-adjusting the waist belt on backplate	Conventional	-	-	-	-	-	-
	Prototype 2	1.38	1.19	-	-		
Ease of assessment of height of waist belt on backplate	Conventional	-	-	-	-	-	-
	Prototype 2	-0.63	2.00	-	-		
Satisfaction of wearing comfort from weight of SCBA	Conventional	0.13	1.36	-1	2	-1.529b	0.126
	Prototype 2	1.38	1.60	-2	3		
Satisfaction of wearing comfort from general fit of SCBA	Conventional	-0.12	1.55	-2	2	-1.802b	0.072
	Prototype 2	1.38	1.19	-1	2		
Stability of wearing SCBA	Conventional	0.63	1.77	-2	3	-2.032b	0.042*
	Prototype 2	2.25	0.89	1	3		
Satisfaction of compression from fit of SCBA	Conventional	0.38	1.41	-1	2	-1.633b	0.102
	Prototype 2	1.63	1.06	0	3		
Agreement on no restriction of general body movement with SCBA	Conventional	0.63	1.77	-1	3	-.513b	0.608
	Prototype 2	1.00	1.20	-1	2		
Agreement on no restriction of lumbopelvic flexion movement with SCBA	Conventional	0.12	1.89	-2	3	-2.032b	0.042*
	Prototype 2	1.75	0.89	0	3		

Question	Type of gear	Mean	SD	Min	Max	Z	Asymp. Sig. (2-tailed)
Agreement on no restriction of lateral flexion movement with SCBA	Conventional	0.38	1.85	-2	3	-1.473b	0.141
	Prototype 2	1.25	1.17	-1	2		
Compatibility with fire helmet in neck motion	Conventional	-0.50	1.41	-3	1	-1.511b	0.131
	Prototype 2	0.25	1.67	-2	3		
Agreement on no restriction of mobility	Conventional	1.13	1.36	-1	3	-1.289b	0.197
	Prototype 2	1.88	0.99	0	3		

Note: N = 8

Score ranged from -3 (strongly difficult/disagree) to 3 (strongly easy/agree).

a Wilcoxon signed-rank test.

b Based on negative ranks.

c Based on positive ranks.

$*p < .05$

Change in Static ROMs with SCBA Prototype 2

As shown in Table 15, because of the means of the two types of fire gear and the direction of the t-value, the dependent t-test concluded that there was a statistically significant improvement in the static ROMs of male participants by the type of fire gear used. While wearing SCBA prototype 2, the static ROM in lateral flexion, neck extension, and lateral neck flexion increased. The distance between the fire helmet and the top of the air cylinder also increased compared with the ROM of a conventional fire helmet; because the distance between the helmet and air cylinder was wider, this would secure more space for the neck extension-related movement. Compared with the mean difference between conventional and prototype 2 designs in the distance from the fire helmet to the top of the air cylinder, the mean difference of the distance in the female participants (mean difference = 18.05 mm) was 36.95 mm shorter than the male participants (mean difference = 54.991 mm). However, the range of neck extension was 6.310° more in the female participants (mean difference = 21.505°) than the males (mean difference = 15.195°). In lateral flexion and lateral neck flexion, the mean differences of static ROM were less than 2°

Table 15

Dependent T-test and Wilcoxon Signed-rank Test Comparison for Static ROM with SCBA and Fire Helmet

Static ROM	Gender	Type of Gear	N	Mean	SD	Std. Error Mean	Mean Diff.	t	Sig. (2-tailed)
Distance from Helmet (mm)	Male	Conventional	6	211.06	39.00	15.92	-54.99	-2.855	0.036*
		Prototype 2		266.05	28.75	11.74			
	Female	Conventional	2	155.73	11.60	4.74	-18.04	-	-
		Prototype 2		173.77	22.79	9.30			
Lateral Flexion	Male	Conventional	6	26.13	7.63	3.12	-7.22	-4.890	0.005**
		Prototype 2		33.35	7.21	2.94			
	Female	Conventional	2	24.72	3.49	1.42	-6.15	-	-
		Prototype 2		30.87	4.87	1.99			
Neck Extension	Male	Conventional	6	32.87	14.90	6.08	-15.19	-4.531	0.006**
		Prototype 2		48.06	10.31	4.21			
	Female	Conventional	2	27.41	16.85	6.88	-21.50	-	-
		Prototype 2		48.91	9.19	3.75			
Lateral Neck Flexion	Male	Conventional	6	30.06	6.20	2.53	-5.58	-2.796	0.038*
		Prototype 2		35.64	7.40	3.02			
	Female	Conventional	2	40.01	15.07	6.15	-6.79	-	-
		Prototype 2		46.80	14.83	6.06			
Static ROM	Gender	Type of Gear	N	Mean	SD	Std. Error Mean	Mean Diff.	Z	Asymp. Sig. (2-tailed)
Lumbopelvic Flexion	Male	Conventional	6	94.81	26.60	-	-9.01	-2.201a	0.028*
		Prototype 2		103.81	18.05	-			
	Female	Conventional	2	89.67	18.49	7.55	-20.09	-	-
		Prototype 2		109.76	18.75	7.65			
Neck Flexion	Male	Conventional	6	50.77	8.92	-	-0.40	“-.943b	0.345
		Prototype 2		51.17	8.82	-			
	Female	Conventional	2	47.58	17.27	7.05	-24.19	-	-
		Prototype 2		71.77	14.46	5.90			

Note: *p < .05. **p < .01. ***p < .001

Negative Ranks_Prototype 2 < Conventional, Positive Ranks_Prototype 2 > Conventional, Ties_Prototype 2 = Conventional.

a Based on negative ranks.

b Based on positive ranks.

between the conventional and prototype 2 designs (1.073° of mean differences in lateral flexion and 1.208° of the mean differences in lateral neck flexion).

A Wilcoxon signed-rank test showed that the type of gear can elicit a statistically significant change in the lumbopelvic flexion of male participants by the type of fire helmet and SCBA designs ($Z = -2.201$, $p = 0.028$); on average, the male participants could bend their waist by 9° more when wearing prototype 2 than when wearing conventional fire gear (Table 15). In the case of female participants, the two female participants' static ROM means in lumbopelvic flexion and neck flexion were 11.082° and 23.787° larger, respectively, compared with the male participants while wearing prototype 2.

4. 2. 2 Design Evaluation of Fire Helmet Prototype 2

Subjective Feedback of Fire Helmet Prototype 2

Figure 27

Key Design Points of Fire Helmet Prototype 2 and Adopted Boa Dial for Fit Adjustment of the Extended Liner

A Wilcoxon signed-rank test for the fire helmet (Table 16) found that the type of gear did not result in a statistically significant change for the participants in

Table 16

Wilcoxon Signed-rank Test Comparison regarding Satisfaction in the Use of Fire Helmet by Type of Gear (Conventional Fire Helmet and Prototype 2)

Question	Type of gear	Mean	SD	Min	Max	Z	Asymp. Sig. (2-tailed)
Donning time (sec)	Conventional	13.13	7.99	4.98	29.85	-1.540b	0.123
	Prototype 2	17.27	8.65	8.51	31.37		
Doffing time (sec)	Conventional	4.06	2.40	2.09	9.24	-2.521b	0.012*
	Prototype 2	7.80	3.16	4.31	13.67		
Ease of donning	Conventional	2.00	1.69	-2	3	-1.717c	0.086
	Prototype 2	-0.37	1.51	-2	2		
Ease of doffing	Conventional	2.38	1.41	-1	3	-2.264c	0.024*
	Prototype 2	1.13	1.73	-2	3		
Ease of access to chin strap for length adjustment	Conventional	2.13	0.99	0	3	-2.070c	0.038*
	Prototype 2	0.75	1.67	-1	3		
Ease of length-adjusting chin strap	Conventional	2.25	0.46	2	3	-1.300c	0.194
	Prototype 2	1.50	1.41	-1	3		
Ease of access to extended liner for fit adjustment	Conventional	-	-	-	-	-	-
	Prototype 2	1.50	1.31	-	-		
Ease of fit adjustment of extended liner	Conventional	-	-	-	-	-	-
	Prototype 2	1.50	1.31	-	-		
Satisfaction of wearing comfort from weight of helmet	Conventional	-0.25	1.58	-3	2	-1.709b	0.088
	Prototype 2	1.13	1.25	-1	3		
Satisfaction of wearing comfort from general fit of helmet	Conventional	-0.75	1.49	-3	1	-1.362b	0.173
	Prototype 2	0.63	1.30	-1	3		
Stability of wearing helmet	Conventional	-0.50	2.51	-3	3	-2.003b	0.045*
	Prototype 2	2.13	0.64	1	3		
Satisfaction of compression from fit of helmet	Conventional	0.25	1.39	-2	2	-1.058b	0.290
	Prototype 2	1.13	1.13	-1	2		
Agreement on no restriction of general neck movement with helmet	Conventional	-0.13	1.81	-3	2	-.256c	0.798
	Prototype 2	-0.12	1.73	-2	3		
Degree of matching of helmet and neck movements	Conventional	-0.62	2.39	-3	3	-1.892b	0.058
	Prototype 2	1.63	0.74	1	3		

Note: N = 8, Score ranged from -3 (strongly difficult/disagree) to 3 (strongly easy/agree).

a Wilcoxon signed-rank test, b Based on negative ranks, c Based on positive ranks.
$*p < .05$

ease of donning the helmet; however, in terms of ease of doffing, the participants were more pleased with the doffing of the conventional helmet design (M = 2.38) than with the helmet prototype 2 design (M = 1.13) based on the paper survey. The participants replied with more satisfaction in ease of access to the chin strap for the conventional fire helmet length adjustment (M = 2.13) than helmet prototype 2 (M = 0.75) but did not show any significant difference in ease of chin strap length adjustment. Regarding prototype 2's extended liner design, the participants responded that access to the liner (M = 1.5) and fit-adjusting it (M = 1.5) were somewhat easy. In addition, the participants showed more satisfaction in wearing the stability of the helmet prototype 2 (M = 2.13) than wearing the conventional design (M = -.50). However, the participants' perceptions did not show statistically significant differences between prototype 2 and the conventional helmet regarding satisfaction in compression from the weight, restriction in neck movement, and accommodation in neck and helmet movement.

Change in Static ROMs with Fire Helmet Prototype 2

As shown in Table 17, while wearing prototype 2 fire helmets, the male participants' neck movements on the sagittal plane (neck flexion and neck extension) were more closely matched to helmet movement than with a conventional fire helmet design. On average, the helmet movement of prototype 2 was 13.01° better matched with the neck movement and flexion movement and 7.92° more matched with the male neck extension movement than the conventional fire helmet design. When wearing the prototype 2, the helmet movements of female participants tended to be more matched with the neck movements than the male participants; females'

Table 17
Dependent T-test regarding the Degree of Movement Matching of Fire Helmet and Neck Movement

Static ROM	Gender	Type of Gear	N	Mean	SD	Std. Error Mean	Mean Diff.	t	Sig. (2-tailed)
Neck Flexion	Male	Conventional	6	20.19	6.41	2.62	13.01	4.650	0.006**
		Prototype 2		7.19	4.40	1.80			
	Female	Conventional	2	62.43	8.37	3.42	49.57	-	-
		Prototype 2		12.86	6.38	2.61			
Neck Extension	Male	Conventional	6	13.07	3.80	1.55	7.92	2.771	0.039*
		Prototype 2		5.15	4.05	1.65			
	Female	Conventional	2	17.28	9.72	3.97	10.50	-	-
		Prototype 2		6.78	2.78	1.13			
Lateral Neck Flexion	Male	Conventional	6	8.72	4.96	2.02	4.41	1.706	0.149
		Prototype 2		4.31	3.17	1.29			
	Female	Conventional	2	14.84	7.28	2.97	9.15	-	-
		Prototype 2		5.68	4.11	1.68			

Note: $^*p < .05$. $^{**}p < .01$. $^{***}p < .001$
Negative Ranks_Prototype 2 < Conventional, Positive Ranks_Prototype 2 > Conventional, Ties_Prototype 2 = Conventional

movements were 36.56° more matched in neck flexion, 2.58° more in neck extension, and 4.75° more in lateral neck flexion.

4. 2. 3 Summary of the Design Validity of Prototype 2

Phase 2 of the present study examined the effects of adding fit-optimizing designs on the improvement in upper body movement and wearing satisfaction with 7 firefighters. Although the satisfaction in the use of prototypes has no large remarkable enhancement compared with conventional designs in many parts of the self-assessment, the satisfaction in wearing stability (secure wearing) showed noticeable enhancement in both the SCBA and fire helmet. Additionally, easier assessment for balancing the length of shoulder straps of SCBA prototype 2 and easier access to the chin strap of helmet prototype 2 were shown when compared with the conventional designs. Regarding the static ROMs in the upper body and neck, six out of seven upper body motions and two out of three movements' synchronization between neck and helmet showed statistically significant increases while wearing the prototypes compared with the conventional SCBA harness and helmet designs. Especially in female participants, the increases were greater compared with the mean difference of the male participants.

CHAPTER 5

Conclusion

The current study identified specific design issues of the conventional SCBA harness and fire helmet that firefighters have with their gear, which can affect their work performance and satisfaction. In addition, the research found that 1) the upper body movements of firefighters were enhanced through the additional fit-adjustable design features, and 2) stability in the wear of SCBA and fire helmet was enhanced by providing the optimal fit. The added fit-adjustable design elements on the SCBA harness and fire helmet were found to improve the static ROMs of the upper body and the movement synchronization between the wearer and gear. In particular, an increase in the mean ROM and the movement synchronization was shown to be greater in female firefighters who complained about the conventional gears' design than their male counterparts. Furthermore, the additional fit adjustable design features were found to improve the stability of wearing the SCBA and fire helmet, but this study could not find statistical differences between the prototype and conventional designs regarding satisfaction in the other uses. As the weak point of the prototype design, the donning and doffing time took longer because of the increased time for fit adjustment compared with the conventional design. However, it is expected that this problem can be relieved as the firefighters learn to work with the added design elements. In addition, the vertically moveable waist belt of SCBA harness prototype 2 design could enhance wearers' activity level while increasing research participants' ROMs in upper body movements. However, such a moveable design feature would decrease a stable placement of SCBA harness. Therefore, further study is also required to figure out how would not fixing the waist belt at a certain height affect the overall safety of firefighters in the field, and how to integrate the optimal design method to maximize both of activity level and safety. Regarding the fire helmet prototype design 2, the extended liner could also increase the activity level of the neck and head while synchronizing the movements between the head and helmet. However, the compatibility issue among the web of the extended liner, face mask, and the hood is still remaining for further investigation.

The major findings of this study imply the possibility of improvement in the mobility and wearing stability of firefighters by applying additional fit-adjustable design which can cover a wider range of firefighters' anthropometry data with more precise fit-adjustable options. A possible change here could be made to the PPE design requirement of the NFPA standards, adding a description of the fit- or size-adjustable availability range of SCBA harnesses and helmet retention systems with more precise size increments to maximize the satisfaction and stability in the wear of the gear compared to the current system. Also, the developed designs of prototypes should meet all safety requirements and tests for practical use. In the prototype development process in this study, the consideration of nonflammable material was excluded to focus on a design improvement of the structural side of the PPE. According to the NFPA, the material properties of the firefighting PPE components should meet a certain heat resistance requirement (NFPA, 2018). Thus, further study with consideration of material properties is required for practical adoption regarding thermal protection.

In this study, a small sample of the firefighter participants was recruited as human subject tests, and a single type of conventional SCBA harness and fire helmet was used for the data collection for satisfaction and motion analysis. Due to the small sample size of the participants (n= 8) in phase 2, who were recruited from local fire departments in New York state, the self-assessment report for general use of the gear failed to elicit statistically valid differences of satisfaction in use by the gender of the participants. Especially, with the small sample size of females (n = 2), the current study could not statistically analyze the differences in the prototype designs' impact on each gender group. However, the data trends of mean values of ROMs in each gender group found in the human performance tests with six male and two female participants shows the difference in an increase in ROMs. Overall, the increase in ROMs was greater in female participants than males. This result may imply the possible benefits of using the prototype with fit optimization design features that may improve female firefighters' mobility. Further studies may validate the findings of this study through a larger scale human performance tests with a greater number of female and male participants in a broader range of age. Such future studies may provide more meaningful implications by investigating how new design of SCBA harness and helmet interact with firefighters in turnout ensembles during active movements in their job-related tasks. Recruiting of participants in the future studies may consider realistic representation of age ratio and gender ratio in US fire service population (about 5-6% of female firefighters). Such research effort of inclusive, user-centered design in consideration of diversity in fire service population may provide opportunity to improve firefighters' comfort, mobility and safety.

The performance test in phase 2 was conducted in lab conditions and the participants performed simple upper body movements. Furthermore, the participants wore minimal baseline clothing (sleeveless top and tights) while testing the conventional fire gears and prototypes, instead of wearing a full turnout ensemble. This is because applying baseline clothing to this test was necessary to isolate the prototype designs' effects from the cumbersome effects of other gear. Clear exposure of retroreflective landmarks for the accurate measurement of static ROM of the body segments was also required by wearing the baseline clothing to track the landmarks attached upon the specific joints and bones. For this reason, there may be a gap between the prototype designs' impact when a firefighter is wearing full PPE gear in the field and when wearing the minimized baseline garments under laboratory conditions. Accordingly, in future studies, complex job-related tasks with turnout ensembles and field tests need to be done.

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Appendix 1

Approval Letters of Institution Review Board for This Study

Cornell University
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Institutional Review Board for Human Participants

NOTICE OF EXPEDITED APPROVAL

To: Yoo jin Chung

From: Andrew Willford, IRB Chairperson

Protocol ID#: 1904008727

Protocol Title: Improving Ergonomic Performance of Firefighters' Personal Protective Equipment

Approval Date: May 13, 2019

Expiration Date: None

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

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

- Yoo jin Chung
- Huiju Park

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

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

1. All consent forms, records of study participation, and other consent materials **must** be held by the investigator for **five years** after the close of the study.
2. Investigators must submit to the IRB any **proposed amendment** to the study protocol, consent forms, interviews, recruiting strategies, and other materials. Investigators may not use these materials with human participants until receipt of written IRB approval for the amendment. For information about study amendment procedures and access to the Amendments application form, please refer to the IRB website: http://www.irb.cornell.edu/forms.
3. Investigators must promptly report to the IRB any **unexpected events** involving human participants. The definition of prompt reporting depends upon the seriousness of the unexpected event. For guidance on recognizing, defining, and reporting unexpected events to the IRB, please refer to the IRB website: http://www.irb.cornell.edu/policy.

4. Upon **conclusion of the study,** the investigator should submit a Project Closure Form: http://www.irb.cornell.edu/forms.

For questions related to this application or for IRB review procedures, please contact the IRB office at irbhp@cornell.edu or 607-254-5162. Visit the IRB website at www.irb.cornell.edu for policies, procedures, FAQs, forms, and other helpful information about Cornell's Human Participant Research Program. Please download the latest forms from the IRB website www.irb.cornell.edu/forms/ for each submission.

Cc: Huiju Park

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Institutional Review Board for Human Participants

NOTICE OF EXPEDITED AMENDMENT APPROVAL

To:	Yoo jin Chung
From:	Andrew Willford, IRB Chairperson
Protocol ID#:	1904008727
Protocol Title:	Improving Ergonomic Performance of Firefighters' Personal Protective Equipment
Approval Date:	October 01, 2019
Expiration Date:	None

Cornell University's Institutional Review Board for Human Participants (IRB) has reviewed and approved the following change(s)/modification(s) to the previously approved protocol referenced above:

Please note the following:
- Addition of new study procedures for evaluating helmet and SCBA harness fit.
- Addition of new questionnaires.

This approval shall remain in effect for the duration of the study.

If you requested modifications to consent form(s), please use the attached revised/new consent form for any future subject enrollment.

If you submitted revised/final versions of interview guides, questionnaires, standard operating procedures, or any other research materials, you have approval to use those materials.

All other study procedures/instruments are to remain unchanged.

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

- Yoo jin Chung
- Huiju Park

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

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

2. Investigators must submit to the IRB any **proposed amendment** to the study protocol, consent forms, interviews, recruiting strategies, and other materials. Investigators may not use these materials with human participants until receipt of written IRB approval for the amendment. For information about study amendment procedures and access to the Amendments application form, please refer to the IRB website: http://www.irb.cornell.edu/forms.
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Cc: Huiju Park