NIOSH Project Form – Project Proposal Information

1. Cover Page

TITLE OF PROJECT (Limited to 60 characters, including spaces. Please Do Not put the project title in ALL CAPS.) Sizing Firefighters and Fire Apparatus: Safe by Design	
PROJ. OFFICER (Last, first middle) Hsiao, Hongwei	**DEGREE(S)** Ph.D., M.S.E., M.A. B.S.E.
POSITION TITLE Branch Chief	**MAILING ADDRESS (Street, city, state, zip code)** 1095 Willowdale Road MS G800 Morgantown, WV 26505
DIVISION/BRANCH Safety Research/Protective Technology	
TELEPHONE (Area code, number, and extension) 304-285-5910	
FAX 304-285-6047	**E-MAIL ADDRESS** HXH4@cdc.gov
HUMAN SUBJECTS: **Will this project utilize human subjects?** **YES:** X **NO:**	**VERTEBRATE ANIMALS:** **Will this project utilize vertebrate animals?** **YES:** **NO:** X
	Species of animals to be used:
	Approximate number of animals to be used:

DATES OF PROPOSED PERIOD OF SUPPORT (MM/DD/YYYY)		**NEW FUNDS REQUIRED (Do not include existing base funding)**				
			PS&B	**Other Intramural**	**Extramural**	**Total**
From:	10/01/2008	**FY2009**				
Through:	09/30/2012	**All Years**				
NEW FTEs	1.0	**% Project Category(s):**	100% Research			
CURRENT FTEs	2.2	**% NORA Sector Grouping:**	100% Services Sector – Public Safety: Firefighting Services (922160)			
TOTAL FTEs (NIOSH)	3.2	**% NIOSH Performance Goal(s):**	100% Research			
Health and Safety Plan needed?		**Yes**		**No**	**X**	**What does Health and Safety plan address (radiation, biologic, chemical, contact/strain injury)? Traumatic Injury**

Project Officer Signature:	**Date**
Division /Laboratory Director Signature: **Approval to forward proposal to Program or Area Manager**	**Date**
NIOSH Program Portfolio Manager Signature: **Project addresses a strategic need of a Sector Program, Cross-Sector Program or Coordinated Emphasis Area and if successful will advance the strategic needs of workers as enumerated in the Program/ Area; submit the Project to the NORA Coordination office for peer review.**	**Date**

2. DESCRIPTION.

Need for the proposed work: There are an estimated 1,136,650 firefighters in the U.S. (National Fire Protection Association [NFPA] 2006a, Karter 2006). The average rate of fatal workplace injuries to firefighters was 16.5 per 100,000 employed for the period 1992-97, which is 3.5 times more than all workers (Clarke and Zak 1999). In addition, firefighters sustain approximately 100,000 injuries per year (Karter and Molis 2003).

Fire apparatus anthropometry is perceived as a safety issue within the fire fighter community. A position paper by the National Fallen Firefighters Foundation (NFFF) in the year 2006 identified the issue of firefighter anthropometry for fire apparatus and equipment design (i.e., cabs, seats, body restraints, egresses, bunker gear etc.) as a pressing concern to prevent firefighters from being killed in crashes and rollover incidents, falls from vehicles, and excessive thermal and chemical exposures (Routley 2006). Recently, five separate professional organizations with interest in fire fighter safety called for an anthropometric survey of U.S. firefighters to address the fire-apparatus design issue and to update the National Fire Protection Association (NFPA) 1901 standards for fire apparatus.

An anthropometric review of fire fighter data suggests further cause for concern. A recent NIOSH study (Hsiao et al. 2002) indicated that on average firefighters are 15 lbs heavier than other occupations combined for males and 22 lbs heavier for females, while current fire apparatus are designed based on the body size information of military personnel of the 70s and 80s. No U.S. national anthropometric database exists for firefighters. This proposal responds to that call. Specifically, the study will establish an anthropometric database of U.S. firefighters for fire apparatus design applications, provide a scientific basis for updating NFPA 1901 fire apparatus standards, and develop 5 improved anthropometric design applications: cab, seat, body restraint, egress, and bunker gear. These improved designs will have immediate and long-term effects on reducing firefighter exposure to transportation-related fatal and non-fatal injuries (through improved driver visibility and control operation, increased post-crash survivability by enhanced seat and body restraint configurations, and improved egress settings) and on mitigating the risk of firefighter health and safety problems that result from poor fit, improper size selection, or the failure to don bunker gear properly.

The study will further 6 NIOSH National Occupational Research Agenda (NORA) program goals: (1) Goal 1.1 "Develop … training information on appropriate body restraints for fire fighters … when operating or riding in emergency response vehicles" and (2) Goal 2.0 "Reduce the incidence and severity of injuries from slips, trips and falls during fire and emergency services rescue operations" for the Service Sector program; (3) Goal 2.3.2 "Identify and evaluate the effectiveness of interventions … in reducing motor vehicle-related injuries and deaths among public safety and emergency response workers, including volunteer response workers such as volunteer firefighters" and (4) Goal 2.3.3 "Develop … information on appropriate body restraints for fire fighters … when operating or riding in emergency response vehicles" for the Traumatic Injuries Cross-Sector program; (5) Goal 2.0 "Develop and evaluate new or modified engineering controls and promote the transfer of effective engineering control measures for safeguarding worker health … formulate a strategy to promote the transfer and translation of research findings into prevention practices and products that will be adopted in the workplace" for the Engineering Controls emphasis area; and (6) Goal 2.0 "Support the development of harmonized personal protective equipment (PPE) standards and test methods to improve the quality, protection, and performance through all PPE lifecycle stages" for the Personal Protective Technology emphasis area.

Project Design and Methods: The specific aims of this project are to (1) determine the critical anthropometric measurements of firefighters relative to the cab geometry of automotive fire apparatus (e.g., cab, seat, body restraints, and egress) and bunker gear, (2) establish an anthropometric database of

firefighters across the U.S., (3) develop multivariate-based accommodation models and anthropometric criteria for the design of cabs, seats, body restraints, egresses, and bunker gear, (4) collaborate with The National Fallen Firefighters Foundation (NFFF), the International Association of Fire Chiefs (IAFC), the International Association of Fire Fighters (IAFF), the Safety Task Force of NFPA 1901 Fire Apparatus Standards Committee, and the Fire Apparatus Manufacturers Association (FAMA) to develop improved fire apparatus, and (5) update the current standards of NFPA 1901 on fire apparatus. This study will use a stratified sampling plan to collect traditional anthropometric data, 3D whole body scans, and workspace data of 900 firefighters from 4 U.S. regions. The number of subjects in each region will be determined by the size of the firefighter population in each region, adjusted by age, gender, and race/ethnicity. The traditional anthropometry will consist of 88 anthropometric dimensions relevant to the design of fire apparatus. A 3D whole body laser scanner will be used to scan 495 of the 900 subjects in 7 posture-by-driving conditions. Additionally, 20 sets of workspace dimensions (i.e., firefighters' ability to reach the steering wheel, operate the brake pedal, and see out of the windshield and mirrors) will be collected in a specially constructed fire apparatus buck for 495 subjects, using a FaroArm. Multivariate-based accommodation models and 3D scans will be used to augment the design of five fire apparatus elements.

Partnership and Transfer of results: NFFF, IAFC, IAFF, NFPA, and FAMA have formed a working group to work with NIOSH/DSR for the research on firefighter anthropometry for the design of fire apparatus. NFFF, IAFC, and IAFF will assist NIOSH in establishing a research consortium and have committed to mobilize national firefighters for the study. Members of the Safety Task Force of the NFPA 1901 Fire Apparatus Committee met with the NIOSH research team in 2007 and have developed a plan to update relevant NFPA standards based on the findings of this study. In addition, the Fire Apparatus Manufacturers Association (FAMA) has actively participated in this proposed project process and has committed to transfer study results to fire apparatus design.

Impact of work: [Intermediate Outcomes] This project will establish a national anthropometric database of U.S. firefighters for automotive fire apparatus design applications and provide a scientific basis for updating automotive fire apparatus-related standards (e.g., NFPA 1901) that will reduce firefighter exposure to transportation-related fatal and non-fatal injuries. [End Outcomes] The improved automotive fire apparatus design will help enhance safe operation (due to improved driver visibility and control operation), increase post-crash survivability (due to enhanced seat and seatbelt configurations; NIOSH 2005a, 2005b), and reduce firefighter exposure to non-fatal injuries, such as falls and contusions (due to improved egress settings and SCBA mounting and donning procedures). The results will have immediate and long-term effects on reducing firefighter injuries. These outcomes can be verified by probabilistic assessment, through reduction in incidence of risk exposures.

Project annual goals (AG) and performance measures (PM): FY09 AG and PM: Complete human subject study protocol and establish data collection logistics. FY10 AG: Develop a U.S. firefighter anthropometric database and a technical report; FY10 PM: Collect anthropometric data from 900 firefighters. FY11 AG: Develop multivariate-based accommodation models and anthropometric criteria for the design of cabs, seats, body restraints, egresses, and bunker gear and a summary report of findings; FY11 PM: Select 3D accommodation models for the design of cabs, seats, body restraints, egresses, and bunker gear. FY12 AG: Disseminate design recommendations and develop apparatus prototypes; FY12 PM: Develop apparatus prototypes and share design recommendations with the fire response community and standards bodies.

PERFORMANCE SITE(S) (organization, city, state)
NIOSH, Morgantown, WV;
Greater Baltimore Fire Department, Baltimore, MD; Greater Phoenix Fire Department, Phoenix, AZ
Greater Chicago Fire Department, Chicago, IL; Greater Dallas Fire Department, Dallas, TX

KEY PERSONNEL (Biographical sketches of the key personnel are attached in the proposal)

NAME	ORGANIZATION	ROLE ON PROJECT
Hongwei Hsiao, Ph.D.	NIOSH/DSR/PTB	Project Officer
Jinhua Guan, Ph.D.	NIOSH/DSR/PTB	Study and data collection coordinator
James Spahr, MPH	NIOSH/DSR/PTB	Partnership coordinator
Tsui-Ying Kau, MPH	University of Michigan	Statistical consultant
Jennifer J. Whitestone, M.S.E.	Total Contact, Inc.	Pilot study coordinator
Service Fellow (to be named)	NIOSH/DSR/PTB	Lead research assistant

3. BIOGRAPHICAL SKETCH.

NAME	POSITION TITLE		
Hsiao, Hongwei	Branch Chief		
EDUCATION/TRAINING			
INSTITUTION AND LOCATION	**DEGREE (If applicable)**	**YEAR(s)**	**FIELD OF STUDY**
National Cheng Kung University, Taiwan	B.S.E.	1977	Engineering
Cornell University, Ithaca, New York	M.A	1985	Product Design
University of Michigan, Ann Arbor, MI	M.S.E.	1988	Industrial Eng.
University of Michigan, Ann Arbor, MI	Ph.D.	1990	Industrial Eng.

RESEARCH AND PROFESSIONAL EXPERIENCE:

A. Positions and Honors.

1977-79 Second Lieutenant and Platoon Leader
1979-83 Engineer and Assistant Manager, Nan Ya Plastics Corp.
1984-90 Teaching Assistant and Research Assistant, Cornell University and University of Michigan
1998-present Adjunct Professor, Industrial Engineering, West Virginia University
1991-93 Industrial Engineer, Safety Controls Section (SCS), PTB, DSR, NIOSH
1993-96 Acting Chief and Chief, SCS, PTB, DSR, NIOSH
1996-present Chief, Protective Technology Branch (PTB), Division of Safety Research (DSR), NIOSH
2003-present Chief, PTB and CDC Distinguished Consultant, NIOSH

Honors, Awards, and Recognition

- Winner of the 2006 NIOSH ALICE HAMILTON AWARD for excellence in engineering and physical science in occupational safety and health.
- Winner of the 2006 NIOSH BULLARD-SHERWOOD R2P TRANSFER OF KNOWLEDGE AWARD.
- Seven times CDC SHEPARD AWARD NIOSH or Division of Safety Research nominee, 2007, 2006, 2004, 2003, 2002, 2001, and 1999.
- HONORARY FELLOW of the Human Factors and Ergonomics Society (US), 2005 – present.
- PROFESSIONAL SERVICE AWARD, the Ergonomics Society (U.K.), 2005.
- FELLOW of the Ergonomics Society (U.K.), 2004 – present.
- CDC SHEPARD AWARD FINALIST, 2004 and 2007.
- Featured in the NEWHOUSE NEWS SERVICE chain on fall injuries and fall prevention research, February 19, 2004.
- Credentialed by the US Government Centers for Disease Control and Prevention (CDC) Executive Resources Board in 2003 as a Silvio O. Conte Senior Biomedical Research Service Fellow and named CDC DISTINGUISHED CONSULTANT
- Winner of the 2003 NATIONAL OCCUPATIONAL RESEARCH AGENDA (NORA) PARTNERING AWARD for worker safety and health.
- Featured in the DOMINION POST NEWSPAPER on unique research on fall protective harnesses, June 10, 2003.
- Featured on the NBC-AFFILIATED WBOY-TV12 MEDIA STATION NEWS on outstanding anthropometry and virtual reality research, June 6, 2003.
- Featured in the JOURNAL FOR MINORITY MEDICAL STUDENTS as one of the 17 CDC CAREER PROFILES FOR PUBLIC HEALTH, March 2003.
- Winner of the International Ergonomics Association (IEA) LIBERTY MUTUAL PRIZE in Occupational Safety and Ergonomics, 2002.

National Advisory Committee Service

- Conference General Chair, 2008 Digital Human Modeling (DHM) for Design and Engineering.
- Drafter for the NIOSH Reduce Occupational Fall Exposure Program within the Personal Protective Technology Cross Sector for the National Academies of Science review, 2007.
- Cochrane review member (Finland) on intervention effectiveness in preventing construction-related injuries, 2006–2007.
- NORA Traumatic Injury Cross-Sector Committee member, 2006-2007.
- Drafter for the NIOSH Falls from Elevation Prevention Program within the Traumatic Injury Cross Sector for the National Academies of Science review, 2006.
- Keynote speaker on falls prevention for the Slip, Trip, and Fall Symposium at the Ergonomics Society annual conference (UK), 2005.
- Keynote speaker, International Advanced Industrial Design Conference, 2004.
- American Society of Safety Engineers Foundation Research Council member, 2004 - present.
- Keynote speaker, International 3D Anthropometry Research and Technology Symposium, 2002.
- Drafter for the NIOSH initiative and strategic goals on Construction Falls Prevention, 2002.
- Member of the U.S. Technical Advisory Group for Personal Equipment for Protection against Falls (TC94/SC4), Delegation to the International Organization for Standardization (ISO), 1999 - present.
- Conference Planning Committee member for the Society of Automotive Engineers annual Digital Human Modeling (DHM) for design and engineering conferences, 1998 – present.
- NORA Program Committee for Musculoskeletal Disorders, 1997-2001.
- Society of Automotive Engineers G-13 committee member for American standards for digital human modeling, 1997 - present.
- Human Factors Society HF-3000 Committee for the American Standards for Anthropometry and Biomechanics, 1997.
- Technical Advisor for the National Research Council Fellowships on Safety Engineering and Ergonomics, 1996-2007.
- The Civilian American and European Surface Anthropometry Resource (CAESAR) Study Partners Committee, 1996-2002.
- Ergonomic Invention Competition Committee, the Laborers Health and Safety Fund of North America, 1995-1997.

Editorial and Scientific Consultation Experience

- Senior Editor, *Journal of the Chinese Institute of Industrial Engineers*, 2007-2008.
- Committee member for grants and fellowships review for the American Society of Safety Engineers Foundation (ASSEF), 2004 - present.
- Editorial board member, *Safety Science* journal, 1999 - present.
- Editorial board member, *Applied Ergonomics* journal, 1999 - present.
- Editorial board member, *International Journal of Industrial Ergonomics*, 1998 - present.
- Editorial board member, *Open Ergonomics* journal, 2007 - present.
- Ad hoc reviewer for *Industrial Health*, 2007.
- Ad hoc reviewer for *SAE Transactions*, 2001-2007.
- Ad hoc reviewer for *Journal of Biomechanics*, 2005 - 2006.
- Ad hoc reviewer for *Ergonomics* journal, 1994, 2002, 2004, and 2005.
- Ad hoc reviewer for *Professional Safety*, 2005.
- Ad hoc reviewer for *International Journal of Human Factors Modeling and Simulation*, 2004.

- Ad hoc reviewer for *Human Factors* journal, 1997, 2001, and 2002.
- Ad hoc reviewer for *Society of Automotive Engineers Technical Paper Series*, 2001 - present.
- Ad hoc reviewer for *Graphical Models*, 2001.
- Ad hoc reviewer for *Human Factors and Ergonomics in Manufacturing*, 2000 - present.
- Ad hoc reviewer for *International Journal of Industrial Ergonomics*, 1996-present.
- Ad hoc reviewer for *Applied Ergonomics*, 1996-present.
- Ad hoc reviewer for the *Human Factors and Ergonomics Society's 39th Meeting Proceedings*, 1995.
- NIOSH Review of OSHA ANPR Ergonomic Standards, 1992 - 1996.

B. Selected 14 most recent peer-reviewed publications (from the author's 105 publications)

1. **Hsiao H**., Long D., Snyder K., 2002, Anthropometric Differences among Occupational Groups, Ergonomics, 45 (2), 136-152.
2. **Hsiao H.,** Bradtmiller B., Whitestone J**.,** 2003, Sizing and Fit of Fall-Protection Harnesses, Ergonomics, 46 (12), 1233-1258.
3. **Hsiao H.,** 2004, Anthropometric Procedures for Design Decisions: From Flat Map to 3D Scanning, Contemporary Ergonomics 2004, 144-148.
4. Lafferty C., Whitestone J., and **Hsiao H**., 2004, Digitization of Farm Tractors and Body Models for the Evaluation of Farm Tractors, SAE Transactions: Journal of Commercial Vehicles 113 (2): 75-85.
5. Zhuang Z., Guan J., **Hsiao H.**, and Bradtmiller B., 2004, Evaluating the Representativeness of the LANL Respirator Fit Test Panels for the Current U.S. Civilian Workers, Journal of the International Society for Respiratory Protection 21, 83-93.
6. **Hsiao H.**, Whitestone J., Bradtmiller B., Whistler R., Zwiener J., Lafferty C., Kau T., and Gross M., 2005, Anthropometry Criteria for the Design of Tractor Cabs and Protection Frames, Ergonomics, 48 (4):323-353, [winner of the 2006 Hamilton Award]
7. Simeonov P., **Hsiao H.**, Dotson B., and Ammons D., 2005, Height Effects in Real and Virtual Environments, Human Factors, 47(2):430-438.
8. **Hsiao H.**, Dotson B., Simeonov P., Ammons D., Kau T., and Chiou S., 2005, Human Responses in Augmented Virtual Mode of Elevation, Ergonomics 48 (10):1223-1242.
9. **Hsiao H.**, Whitestone J., and Kau T., 2007, Evaluation of Fall-Arrest Harness Sizing Scheme, Human Factors, 49 (3):447-464. [selected for press release by the Human Factors and Ergonomics Society: http://www.hfes.org/web/DetailNews.aspx?ID=131; CDC Shepard Award finalist]
10. van der Molen H.F., Lehtola M.M., Lappalainen J., Hoonakker P.L.T., **Hsiao H.**, Haslam R., Hale A.R., Verbeek J., 2007, Interventions for Preventing Injuries in the Construction Industry, Cochrane Database of Systematic Review, Issue 4., No.:CD006251. DOI:10.1002/14651858.CD006251.pub2.
11. **Hsiao H.**, Hause M., Powers J., Kau T., Hendricks C., Simeonov P., 2008 Effect of Scaffold-End-Frame Carrying Strategies on Worker Stepping Response, Postural Stability, and Perceived Task Difficulty, Human Factors 50 (1), [in press; February 2008].
12. **Hsiao H.**, 2008, Engineering Technologies in Practice: the NIOSH Experience, Professional Safety, 2008 (4) [in press; April 2008].
13. **Hsiao H.**, 2008, Evaluating Technology And Research Knowledge Gaps For Prevention Of Falls From Scaffolds, Contemporary Ergonomics [in press; April 2008].
14. **Hsiao H.**, Simeonov P., Pizatella T., Stout N., McDougall V., Weeks J., 2008, Extension-ladder safety: solutions and knowledge gaps, International Journal of Industrial Ergonomics [in press].

C. Research and Support.

The author has been the project officer or advisor for more than 50 NIOSH projects since 1991. Four selected recent projects and relevant support work are presented below.

Project 1: Harness Design and Sizing Effectiveness (2003-2008). Role: Project Officer
The overall goals of this project are to develop an effective harness sizing system that would accommodate the construction worker population in the country and to formulate anthropometric guides for the design of improved fall-arrest harnesses. Currently, two harness manufacturers are redesigning harnesses, using the theories and data that were established by the research team. [Received IEA 2002 Liberty Mutual Prize and NIOSH 2006 Bullard-Sherwood r2p Award; $600K + S&B]

Project 2: Anthropometry of Agriculture Population (2003-2004). Role: Project Officer
The project studied whole body anthropometry of agriculture workers for the design of farm tractors and roll-over protective structures. Anthropometric criteria and 15 representative human models were developed for the design of farming tractors to increase the safety of tractor operation. The research results are currently being used by the SAE J2194 standard committee to revise the tractor cab dimension standard. [Received NIOSH 2006 Alice Hamilton Award; $400K + S&B]

Project 3: Truck Driver Anthropometric and Workspace Survey (2007-2010). Role: Co-Project Officer
This project will establish a large-scale anthropometric database of truck drivers for the design of efficient truck cabs to enhance safe truck operation, increase post-crash survivability, and reduce driver exposure to non-fatal injuries. Society of Automotive Engineers (SAE) and the truck manufacturing industry will translate research findings into the next generation of cab designs and cab-occupant-environment standards. [$1M + S&B; SAE and 4 truck manufacturers provided additional funds through letters of agreement]

Project 4: Effectiveness of Extension-Ladder Safety Innovations (2008-2011). Role: Project Officer
This project will establish engineering solutions to minimize the possibility of workers making unsafe choices or actions, and thus reduce fall-from-ladder incidents. Specifically, the project objectives are to (1) research and develop low-cost user-friendly angle-of-inclination indicators or strategies for setting correct angle of ladder inclination, (2) develop and evaluate ladder-top configurations or devices to ease the transitioning from a ladder to an elevated surface, (3) develop and evaluate the effectiveness of convertible "Swiss-Army-knife" ladder designs or concepts with essential ladder stabilizers to support safe practices, and (4) develop a graphic-oriented practical guide on ladder safety innovations, ladder use, maintenance, and mechanical-flaw detection and validate the effectiveness of a ladder safety practice guide. American Ladder Institute, the ANSI A14 committee on ladder accessory standards, and two construction trades will translate research findings into the ladder designs and safety practice standards. [$1M + S&B]

Support work 1: Developed functional and technical specifications for the NIOSH Anthropometry, Digital Modeling, and Virtual Reality laboratories for anthropometry research applications.
Support work 2: Supervise 30 staff members for engineering research, including anthropometric projects in harness sizing, farm tractor workspace design, firefighter glove sizing, truck cab, and eyewear protection.
Support work 3: Delivered invited lectures on anthropometry theories and applications for occupational safety at the Finnish Institute of Occupational Health (1998), Univ. of Cincinnati (1998), WVU Medical School (2000), Cornell University (2001), Purdue University (2003), International Fall Protection Society (2003), Univ. of Michigan (2004), West Virginia University (2005), Univ. of Calif. Berkley (2006), and National Taiwan University (2007).

Project Proposal, Personnel Plan, and Budget

4. RESOURCES

FACILITIES: Specify the facilities to be used for the conduct of the proposed project. Indicate the performance sites and describe capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Under "other" identify support services such as machine shop, electronics shop, and specify the extent to which they will be available to the project. Use continuation pages if necessary.

Laboratory: (Provide room numbers where the work will be performed)
The Anthropometry Research Laboratory (Room H1502) and Safety Engineering Laboratory (Room H1610) at the NIOSH Morgantown facility will be used to practice and refine data collection procedures. Actual data collection on human subjects will take place in a rental space situated nearby a major fire department in each of four Census regions of the United States.

Field: (Identify workplaces or other sites to be used.)
Four data collection sites are being targeted for this study: Baltimore, MD; Phoenix, AZ; Chicago, IL, and Dallas, TX.

Animal: (Provide room numbers where the work will be performed. Provide requests for special care and handling of the animals or for special equipment needed in the animal facilities.)
Not Applicable.

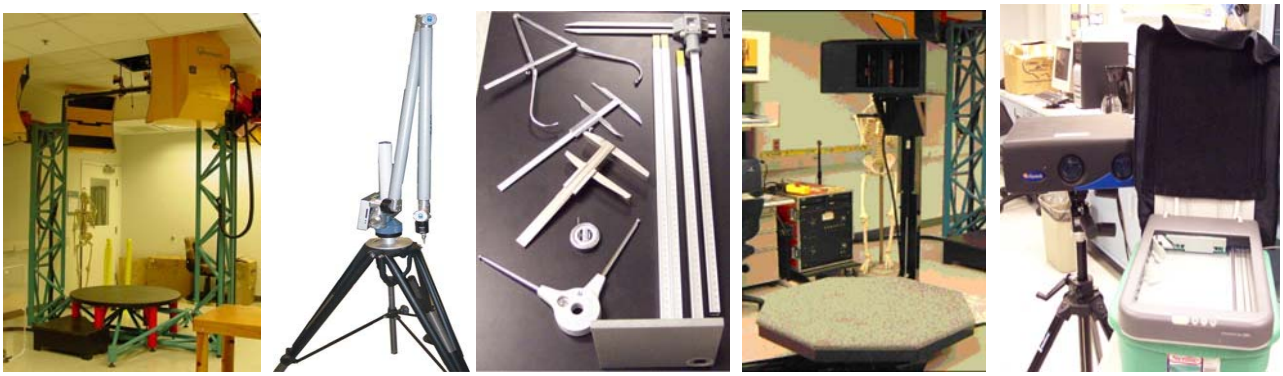
Other:
The NIOSH machine shop (Room B204) will be used to modify a prototype automotive fire apparatus cab for collecting workspace data. In addition, the NIOSH Protective Systems Laboratory (Room H1504) will be used to develop control sensors and cab-component adjustment mechanisms which will be integrated into the prototype fire-apparatus cab, to allow test subjects to fully evaluate cab, seat, egress, and seatbelt configurations.

Major equipment: List the most important equipment items already available for this project, noting the location and pertinent capabilities of each.
A 3D whole-body laser scanner WB4 (Cyberware Inc., Monterey, California) will be used in data collection (Figure 1a). The scanner, one of about twelve WB4 whole body scanners available in the United States, is currently housed in the Division of Safety Research (DSR) Anthropometry Research Laboratory (Room 1502), Morgantown, West Virginia. The scanner uses four scan heads to capture the surface contour of the human body in 17 seconds. The scanner heads start above the head level and move downward at a constant rate. The scan heads contain safe low power visible and invisible (infrared) lasers that are swept across the human body to record dimensions and brightness. The scanning system is accurate to an average error factor of 2.9 mm, with an error range from +6 mm to -6 mm (Hsiao et al. 2003).

A portable Platinum 8-foot FaroArm (FaroArm Technologies, Lake Mary, Florida) will be used to measure cab accommodation values for individual subjects. The FaroArm is a seven-axis articulating measurement device that is capable of measuring an area of a 121 cm in radius with accuracy to 0.0005 mm (Figure 1b).

A set of anthropometers and calipers (GPM, Switzerland) and a Toledo scale (Mettler-Toledo Inc., Worthington, OH) will be used to collect traditional anthropometry measurements and body weight (Figure 1c).

A Cyberware head scanner (Figure 1d) and a hand scanner (Figure 1e) will also be used to produce detailed surface images of heads and hands. These scans will be used to determine the geometry and volume of the head and hand so that accurate sizing information can be established for firefighter head gear and protective gloves.



(a) (b) (c) (d) (e)

Figure 1. The Anthropometry Research Laboratory (Room 1502) and Safety Engineering Laboratory (Room 1610) at the NIOSH Morgantown facility are equipped with (a) a Cyberware whole body laser scanner (WB4), (b) a FaroArm digitizer, (c) a set of anthropometers and calipers, (d) a head scanner, and (e) a hand scanner for this proposed project

5. The Project Plan: A) Overall Objective and Specific Aims; B) Background and Significance; C) Preliminary Studies/Progress Report; D) Hypothesis, Design Concept, Problem; E) Study Design and Methods; F) Human Subjects, OMB, and Staff Health and Safety; G) Vertebrate Animals.

A. Overall Objective and Specific Aims

A.1. Overall Objective

The overall objective of this study is to establish an anthropometric database of U.S. firefighters that accurately measures the enormous variations in body sizes between individual firefighters by gender, race and age. Specifically, the study will establish an anthropometric database of U.S. firefighters for fire apparatus design applications, provide a scientific basis for updating NFPA 1901 fire apparatus standards, and develop 5 improved anthropometric design applications: cab, seat, body restraint, egress, and bunker gear. These improved designs will help enhance safe operation (due to improved driver visibility and vehicle control operation), increase post-crash survivability (due to enhanced seats and body restraint configurations), mitigate fall risks (due to improved ingress/egress settings), and reduce firefighter exposure to safety problems that result from poor fit, improper size selection, or failure to don bunker gear properly.

A.2. Specific Aims

To accomplish the Overall Objective, five specific aims are proposed: (1) determine the critical anthropometric measurements of firefighters relevant to the design of cab, seat, body restraint, egress, and bunker gear, (2) establish an anthropometric database of firefighters across the U.S., (3) develop multivariate-based accommodation models and anthropometric criteria for the design of cab, seat, body restraint, egress, and bunker gear, (4) develop improved apparatus through collaboration with NFFF, IAFC, IAFF, NFPA, and FAMA, and (5) update the current NFPA 1901 standards on fire apparatus. Each of the aims is described in greater detail below.

<u>A.2.1. Determine the critical anthropometric measurements of firefighters relevant to the geometry and use of cab, seat, body restraints, egress, and bunker gear.</u>

This project will convene a consortium meeting of the major automotive fire apparatus manufacturers and firefighter associations to finalize the critical anthropometric measurements related to cab, seat, body restraints, egress, and bunker gear accommodation (Figure 2 a-e). The five major apparatus elements were selected based on an IAFC-NFFF-FAMA-NIOSH group discussion and consensus expert opinion in August 2006 and the FAMA Technical Committee report on anthropometry for safer apparatus design, dated September 16, 2006. Fifty-six body landmarks, 88 anthropometric measurements, and 20 workspace measurements will be collected; the definitions of these measurements are available from the following sources: (1) Guan et al. 2006 (truck cab and seat study), Hsiao et al. 2005 (farm tractor cab study), and Sanders and Shaw 1985 (truck cab study) for cab, seat, and egress design applications and (2) Hsiao et al. 2003 and 2007 (fall-arrest harness studies) for body restraints and bunker gear applications.

Figure 2a. Improved cab designs which can accommodate firefighters with variations in body sizes will help enhance safe operation of fire apparatus due to improved driver visibility and vehicle control operation.

Figure 2b. Enhanced seat configurations which can accommodate firefighters with variations in body sizes will help increase post-crash survivability.

Figure 2c. Enhanced body-restraint configurations which can accommodate firefighters with variations in body sizes and shapes will help increase post-crash survivability.

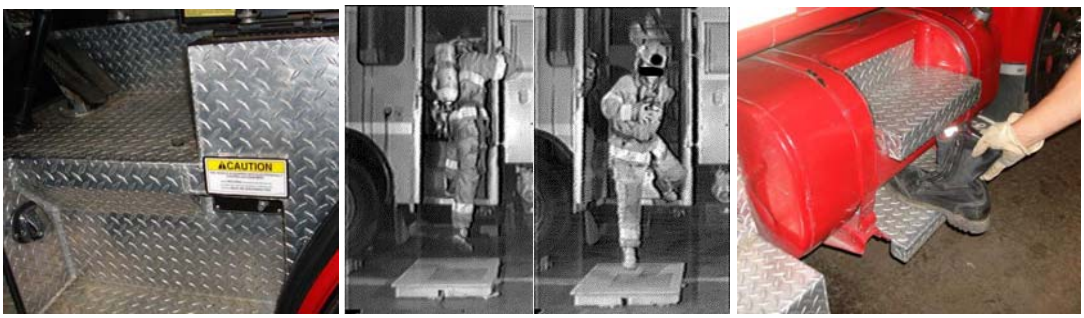


Figure 2d. Improved ingress/egress settings which can accommodate firefighters with variations in body sizes will help mitigate fall risks.

Figure 2e. Updated firefighter anthropometry, which can improve the sizing of protective gear, will help reduce firefighter exposure to health and safety problems from poor fit (due to variations in body sizes and shapes), improper size selection, or the failure to don bunker gear properly.

A.2.2. Establish an anthropometric database of firefighters across the U.S.
This database will consist of anthropometric data for 900 U.S. firefighters (please see section E.1. for sampling planning). Specifically, the database will contain three types of data: (1) body dimensions collected by the traditional anthropometric method (anthropometer, caliper, and tape measure) for 900 participants, (2) 3D scans of 495 participants in 7 posture-by-dress combinations [i.e., 2 postures (standing and sitting) by 3 conditions (without protective gear, with protective clothing only, and with protective clothing and SCBA) plus a comfortable driving posture while wearing protective clothing], plus head and right-hand images, and (3) cab workspace data measured for 495 participants with a FaroArm while the firefighter is seated in a simulated cab. Traditional anthropometric measurements will be used to establish extreme values as anthropometric criteria for the design of certain apparatus elements. For instance, shoulder width and hip width are needed to define the minimum width of egresses. The scans will be used to evaluate the fit of bunker gear, seat, body restraint, and cab to firefighters in terms of firefighter body shape and size, and to develop digital models for computerized product design applications. The "workspace data" will be used to define the functional accommodation of cab apparatus arrangement.

A.2.3. Develop multivariate-based accommodation models and anthropometric criteria for the design of cabs, seats, body restraints, egress/ingress, and bunker gear.
This project will develop a multivariate 15-man accommodation model by applying the Multivariate Anthropometric Method (MAM). This model will consist of all individuals representing distinct body types and dimensions that must be accommodated by ergonomically efficient fire truck cabs, seats, body restraints, egress/ingress, and bunker gear. Each of the 5 fire apparatus elements may or may not have the exact same 15-man model. (Please see E.7.3. Develop anthropometric models under section ***E.7. Data Analysis*** for detailed model descriptions.)

A.2.4. Engage in joint developments with FAMA, NFFF, IAFC, IAFF, and NFPA to develop improved automotive fire apparatus elements.
This project will engage major U.S. fire apparatus manufacturers (members of the FAMA) in developing new-generation cabs, seats, body restraints, egress, and bunker gear for firefighters. User input from NFFF, IAFC, IAFF, and NFPA will be incorporated in the process along with traditional anthropometry data, 3D scans, and cab accommodation models, for design applications.

A.2.5. Evaluate the current standards of the NFPA 1901 on firefighter automotive fire apparatus.
The NFPA 1901 standard on automotive fire apparatus dimensions was derived from the SAE J833 standard on general truck dimensions. To quantitatively determine whether the SAE J833 standard needs to be updated, the physical dimensions measured in this study (i.e., Specific Aims A.2.2. and A.2.3. above) will be compared with their corresponding data in the current SAE J833 standard. Findings from these comparisons will be used to justify updating the SAE standard. It is anticipated that a completely new standard on firefighter automotive fire apparatus dimensions will become necessary. The Safety Task Force of NFPA 1901 Fire Apparatus Standards Committee and the Fire Apparatus Manufacturers Association (FAMA) have jointly advocated for an anthropometric survey of U.S. firefighters to address the automotive-fire-apparatus design and specification issue, including body restraint, egress/ingress, and bunker gear standards.

In addition, the firefighter's eye, head, knee, stomach, and selected body landmark positions while assuming a comfortable seated driving pose will be used to establish supplemental NFPA 1901 standards that

correspond to SAE J941 standard on eye-position range, SAE J1052 standard on head-position range, SAE J1521 standard on shin-knee-position for clutch and accelerator, SAE J1522 standard on stomach-position range for driving wheel, and SAE J1517 standard on driver-selected seat-position for 95% of current firefighters. Currently, no firefighter anthropometry information is available for the configuration of driving wheel, seat, and cab space for fire apparatus in the NFPA 1901 standards.

B. Background and Significance

B.1. Need for the Research

There are an estimated 1,136,650 firefighters in the U.S. (NFPA 2006a, Karter 2006). The average rate of fatal workplace injuries to firefighters was 16.5 per 100,000 employed for the period 1992-97, compared to a rate of 4.7 per 100,000 for all workers (Clarke and Zak 1999). Firefighter non-fatal injuries are also high, occurring approximately 100,000 times per year (Karter and Molis 2003). The National Fallen Firefighters Foundation (NFFF) year 2006 white paper reported that firefighter anthropometry for fire apparatus and equipment design (i.e., cabs, seats, body restraints, egresses, bunker gear etc.) is a pressing issue to prevent firefighters from being killed in crashes and rollover incidents, falls from vehicles, and from excessive thermal and chemical exposures (Routley 2006). Various concerned parties-- the NFFF, International Association of Fire Chiefs (IAFC), International Association of Fire Fighters (IAFF), Safety Task Force of NFPA 1901 Fire Apparatus Standards Committee, and Fire Apparatus Manufacturers Association (FAMA) -- jointly advocated for an anthropometric survey of U.S. firefighters to address the fire-apparatus design issue.

In the NFFF white paper issued in 2006, it was noted that the current configuration of crew-compartment seat arrangements and seatbelt placement made it difficult or impossible for firefighters wearing protective clothing to reach and fasten their seatbelts while operating automotive fire apparatus. In addition, a quarter of fire departments reported that their firefighters had experienced difficulties in buckling themselves in their current fire trucks (Peterson et al. 2006). The problem of accessing seat belts was further complicated by the presence of self contained breathing apparatus (SCBA), which is integrated into the backs of many fire truck seats. The typical SCBA would add an additional set of shoulder straps and a waist belt to be accommodated, as well as several hoses, attachments and accessories. The joint stakeholders emphasized that all of these factors must be taken into consideration in the design of cabs, seats, seatbelts and even SCBA straps, and have requested that NIOSH consider this matter as urgent and critical. Fire Service stakeholders have also noted that average firefighters wearing full structural firefighting gear today are considerably more bulky than previous generations of firefighters, and current cab, seat, egress, and space arrangements may be inadequate for many users. They understand that this part of the problem requires a detailed anthropomorphic analysis of firefighter bodies, both with and without protective gear. The recent NIOSH publication on anthropometry among occupational groups, based on the National Health and Nutrition Examination Survey (NHANES) data, confirmed that on average firefighters are 15 lbs. heavier than all occupations combined for males and 22 lbs. heavier for females (Hsiao et al. 2002). Most of the NFPA standards have used SAE J833 for reference. Some apparatus manufacturers have also used military standards for guidance. However, the information as adopted in the automotive apparatus standard NFPA 1901 is becoming outdated and the military populations do not adequately represent firefighter populations, which are different in age, size, and weight composition.

Problems in human-cab interaction are known to contribute to fatal and non-fatal vehicle incidents. For example, good visibility is essential for safe operation of a motor vehicle (Henderson et al. 1983, Senter 1998). To design a safe fire engine with good visibility, current information on driver anthropometric

dimensions and his/her relationship to the cab interior geometry are required (Figure 2a). In addition, adequate seat configuration and restraint use reduce the chance of injury in fire-engine collisions (Campbell 1999; NIOSH 2005a, 2005b). To assure proper seat adjustment and encourage restraint use to prevent ejection and entanglement, designers need accurate data on firefighters' body size and cab interior data in order to design effective seat and restraint systems and maintain sufficient survival space (Figures 2b & 2c). Furthermore, to reduce falls and slips during ingress or egress of a fire engine cab, designers need to know relevant firefighter anthropometry with and without bunker gear, such as a firefighter's leg length, stepping height, shoulder width, hip width, and overhead finger-tip-reach length, to design sound firefighter-egress interface systems (English 1993, Giguere and Marchand 2005; Figure 2d). Finally, three-dimensional body shape and size information is needed to determine effective bunker-gear sizing-systems and the fit of SCBA straps to firefighters (Figure 2e).

Anthropometry databases on U.S. firefighters are very limited. Veghte (1991) reported 30 traditional measurements of 20 firefighters with a focus on protective clothing application. Hsiao et al., (2002) reported 14 traditional measurements of 189 protective services persons (including firefighters) based on the NHANES database of 1988-1994. These studies were conducted in an era when 3D scanning technology was not available and the results are also limited by their small sample size. With the emergence of 3D laser scanning technology, detailed information about human body dimensions and contours can be collected for multiple design applications in a few seconds. A recent British anthropometry survey of 316 female firefighters reported data of 61 traditional measurements for personal protective equipment design use (Sterling 2006). However, the study neither included workspace data for cab design nor 3D body scans for restraint system design applications.

The recent Civilian American and European Surface Anthropometry Resource (CAESAR) database is an excellent resource for some product design applications. However, CAESAR has several major limitations in its applications to automotive fire apparatus designs. First, this study is a generic anthropometric study whose subjects are drawn from 15 sectors of industry. Not one firefighter was included in the total sample of 2,353 subjects. It has been shown that the U.S. firefighter population is taller and heavier than the general U.S. population (Hsiao et al. 2002); it is inappropriate to apply data from a generic survey to a specific population. Second, the CAESAR is not designed for fire engine design applications and, as a result, does not have critical information for fire-engine-design purposes. For example, CAESAR does not have such measurements as functional leg reach to brake and clutch, functional hand reach for controls, and stomach–steering wheel clearance. Third, it does not have the scans of a person wearing protective gear.

The present research proposal represents a step forward for a large-scale survey and in the use of advanced technology (e.g., 3D whole body laser scanner and 3D FaroArm digitizer) in support of an anthropometric study of American firefighters. With the emergence of 3D scanning technology, anthropometric research is in a transitional period to advance from traditional 2D measurements to 3D measurements. This study will employ both traditional anthropometry and laser scanning technology in data collection. Traditional anthropometry will ensure easy comparison of data between this and previous studies, whereas 3D scan information (body dimensions, body contours, and spatial relations between body parts) will be used for advanced anthropometric analysis, computer simulation, and modeling.

Finally, this study will employ the multivariate anthropometric method (MAM) in data analysis – an advanced approach that has been used for aircraft cockpit accommodation and farm tractor design evaluation purposes (Zehner et al. 1992; Hsiao et al., 2005). MAM uses principal component analysis

(PCA), a type of factor analysis, as a data reduction method to reduce the number of variables measured in a design application (such as cab operation space, restraint system configuration) to a small, more manageable number of variables called components. The first component describes the linear combination of the original variables that account for the maximum amount of variance. The second component describes a second linear combination accounting for the second largest amount of variance. The third component accounts for the third largest variance, and so forth. These components can be described as a distribution in the shape of an ellipse (2-components) or an ellipsoid (3-components) that account for a certain percentage (ideally 95% and above) of an entire population. Specific data points along the perimeter of the ellipse or the surface of the ellipsoid can be chosen. For each data point, an individual subject closest to the data point will be selected for model development. These individuals represent distinct body types or shapes that must be accommodated by new cab or restraint system designs.

In fact, the project will pursue the development of a new multivariate-based standard on fire-engine cab design and protective gear development in conjunction with the NFPA 1901 Committee. Individual models for eye, head, shin-knee, stomach, and selected seat positions will be developed. Seat, seatbelt, and egress/ingress design criteria will also be established along with the FAMA technical committee. The 3D scans of the firefighter will also be used for the design and sizing of protective gear -- clothing, helmets, fire boots, and gloves.

B.2. Likelihood of success

The likelihood for NIOSH to successfully complete this project is very high because: (1) the study has management support to further 6 NIOSH National Occupational Research Agenda (NORA) program goals; (2) the Division of Safety Research has a strong research team in anthropometry; (3) the anthropometry team is well-positioned to use cutting-edge 3D technology for anthropometric research; (4) the team has an excellent record of project management, collaborative research, and publications; (5) a partnership with NFFF, IAFC, and IAFF has been established to identify fire apparatus design criteria and to recruit firefighter subjects; and (6) a partnership with FAMA and NFPA has been formed to transfer study results into fire-apparatus design practice and standardization. Items (1), (5), and (6) have been described in pages 3 and 4. An elaboration of items (2), (3), and (4) is presented below.

<u>B.2.1. Division of Safety Research (DSR) anthropometry research team.</u>

The DSR anthropometry program has a strong research team.

Hongwei Hsiao, the project officer, is a senior researcher and a NIOSH Branch Chief with an international reputation in the field of human factors and safety engineering. He has initiated and led research in applied anthropometry in the Protective Technology Branch (PTB) since 1991. He has published more than 100 papers, including anthropometric applications for industrial safety. He also has served on 5 national research committees, 4 journal editorial boards, and ad hoc review boards for numerous journals. His publication in harness fit and sizing has been awarded the prestigious International Ergonomics Association 2002 Liberty Mutual Award. His research in harness design criteria also has been awarded the 2006 Bullard-Sherwood r2p Award and has been nominated for 2007 CDC Shepard Award. In addition, his research in tractor operator anthropometry and cab configuration has been awarded the distinguished NIOSH 2006 Alice Hamilton Award. He has also been named CDC Distinguished Consultant, Fellow of the Ergonomics Society (U.K.), and Honorary Fellow of the Human Factors and Ergonomics Society (U.S.) for his outstanding record of accomplishment in anthropometric research.

Jinhua Guan, a NIOSH service fellow, has more than eight years of experience in anthropometry research, serving as a lead investigator for a newly funded 4-year national anthropometry survey of truck drivers and their workspace.

James Spahr also has six years of experience in anthropometry research. He is the project officer of a current PTB fire-fighter glove sizing study. He also serves as a lead investigator for a newly funded 2-year anthropometry study for mesh glove sizing and design for meat-processing workers.

Richard Whisler and Joyce Zwiener have a great deal of experience in conducting traditional measurements, 3D scanning, and post-scan image processing/extraction. They have a combined record of conducting traditional anthropometric measurements and laser scanning for hundreds of subjects as well as accumulating thousands of hours of experience in post-scan image processing and digital data extraction.

Ying Kau has a great deal of experience in survey planning, experimental design, and various statistical consultations. She has provided statistical support to all engineering projects in PTB since 2002.

Jennifer Whitestone has extensive experience in 3D anthropometry research and applications. Her specialty is in the collection and application of body size data toward problems in the design of personal protection devices and other arenas. She has worked on 3D anthropometry since 1996 and has worked with the NIOSH anthropometry research team on projects related to the design of fall-arrest harnesses and farm tractors, since 1999. She currently is leading a pilot study of firefighter anthropometry for seatbelt design.

Doug Cantis and John Powers have a great deal of experience in developing physical mockups and data collection sensors and devices. They have a combined record of 20 years in supporting PTB for various research projects that were conducted in the field and in the laboratory.

B.2.2. Cutting edge technology

The DSR/PTB anthropometry laboratory is equipped with the most advanced technology in 3D anthropometric research. The focal technology for the project is a whole body 3D laser scanner (Model WB4; Cyberware, Monterey, CA), which is ready for mobilization for this project (See Figure 1a). This WB4 scanner is one of about 12 WB4 scanners currently available in the United States. In addition, the lab has a FaroArm, Bronze series (Figure 1b; FaroArm Technologies, Lake Mary, Florida) for workspace and cab interior geometry data collection. The lab also has a Head and Face 3D Laser Scanner (Cyberware, Monterey, CA; Figure 1d), and a hand scanner (VisImage Systems Inc. Toronto, Canada; Figure 1e) for additional detail hand and head scans.

B.2.3. Project management skills and publication records

The anthropometry team has a successful record of project management and research publication. The research areas in which the team was engaged in the past included, but were not limited to, farm tractor cab workspace measurement, agricultural worker anthropometry, harness fit and sizing, meat-processing glove evaluation, and truck driver anthropometry and workspace evaluation. Some applications in which the team has completed or is currently conducting research are as follows:

- *Agricultural worker anthropometry and farm tractor cab and protective envelope.* Farm tractor rollover is the most common event leading to death and injuries in the agricultural industry. Volumetric and anthropometric analysis of farm tractor cabs and the protective envelope provided by the rollover protective structures (ROPS) have been identified as areas that would benefit from

updated, accurate anthropometric data in the design process. This project focuses on formulating anthropometric criteria for the design of safer farm tractors with more effective ROPS. The results have been published in the Ergonomics Journal [Hsiao et al. 2005].

- *Whole body fall-arrest harness sizing.* This project is intended to establish a sizing system for the design of fall-arrest harnesses for American civilian workers, and to formulate an anthropometric guide for users to select the correct size of fall-arrest harnesses for work. Currently, the design of a whole body harness depends on anthropometric data collected in the 1970s on military personnel in the country. Military data does not represent the civilian population because of the military's relatively stringent entry requirements. To overcome this problem, this project collected anthropometric data from 316 civilian subjects. It used 3D scanning technology to scan subjects in 3 postures. Two 3D shape-analysis approaches (Bounding Box Method and Ellipse Fourier Analysis Method) were developed to analyze harness fit to human torsos. A provisional sizing scheme with an algorithm that describes the human torso-shape-and-size distribution and a set of recommendations for producing vest-type harnesses were published in Human Factors journal [Hsiao et al. 2007]. The sizing scheme has been further applied to a sample of 600 CAESAR subjects to establish the adjustment range for each harness component. Mine Safety Appliances Co. and DBI-SALA Fall Protection Inc. are using the information for prototype development for a new generation of harnesses.

- *Glove sizing and fit.* The purpose of this project is to develop a sizing and fit model for protective gloves used by fire fighters. Advanced digital human scanning and modeling technologies are used to evaluate and improve the traditional fit assessment of protective gloves. Specifically, this project investigates (1) methods for data collection and the ability of 3D hand scanners to provide accurate hand anthropometry data; (2) methodologies for assessing fit of protective gloves using 3D anthropometric data; (3) the use of shape analysis for improving the design of protective gloves. This project will be completed in September 2008.

- *Truck driver anthropometry and workspace survey.* Truck drivers were 6.5 times more likely to be killed in job-related incidents than the average worker. Fatal traffic crashes led all other work-related fatal events among truck drivers, claiming 6,884 lives during 1992-2000. This project is to establish an anthropometric and workspace database for U.S. truck drivers. This database will be used to upgrade standards for designing ergonomically efficient truck cabs, which will benefit 1.6 million workers employed as heavy and tractor-trailer truck drivers. Ergonomic cabs will enhance safe operation, increase post-crash survivability, and reduce truck drivers' exposure to non-fatal injuries, such as sprains and strains and contusions. The project is in the first year of a 4-year effort. The project has an established partnership with four major U.S. truck manufacturers and the Society of Automotive Engineers to directly transfer the results of this study into U.S. truck cab designs.

- *Selected recent publications and presentations relevant to this proposal*

Hsiao H, Long D, Snyder K [2002]. Anthropometric differences among occupational groups, Ergonomics *45*:136-152.

Hsiao H, Bradtmiller B, Whitestone J [2003]. Sizing and fit of fall-protection harnesses, Ergonomics *46*:1233-1258.

Spahr J, Kau T, Zwiener J, Whisler R, Hsiao H [2003]. Relative change in hand size over time: implications for glove-size schemes and labeling for end-users, poster and special presentation, 2003 National Occupational Research Agenda (NORA) Symposium, June, Washington, D.C.

Spahr J, Kau T, Hsiao H, Zwiener J [2003]. Anthropometric differences among Hispanic occupational groups. 2003 National Occupational Injury Research Symposium (NOIRS), October 28-30, Pittsburgh, PA.

Guan J, Hsiao H, Current R, Powers J, Ammons D, Cantis D, Spahr J [2003]. Traumatic injury potential to seat-belted operator during a rearward overturn of a ROPS-equipped farm tractor, 2003 National Occupational Research Agenda (NORA) Symposium, June, Washington, D.C.

Hsiao H [2004]. Anthropometric procedures for design decisions: from flat map to 3D scanning, Contemporary Ergonomics, 144-148.

Zhuang Z, Guan J, Hsiao H, Bradtmiller B [2004]. Evaluating the representativeness of the LANL respirator fit test panels for the current U.S. civilian workers, Journal of the International Society for Respiratory Protection *21*:83-93.

Friess M, Rohlf FJ, Hsiao H [2004]. Quantitative assessment of human body shape using Fourier analysis, SPIE—The International Society for Optical Engineering Conference, January 18-22, San Jose, CA.

Lafferty C, Whitestone J, Hsiao H [2004]. Design feature envelopes for the tractor workspace, SAE Digital and Human Modeling for Design and Engineering Conference and Exposition, June 14-16, Rochester, Michigan.

Hsiao H, Whisler R, Kau T, Zwiener J, Guan J, Spahr J [2005]. Constructing new harness fit charts using 3D anthropometric information, Contemporary Ergonomics: 3-7.

Hsiao H, Whitestone J, Bradtmiller B, Zwiener J, Whisler R, Kau T, Gross M, Lafferty C. [2005]. Anthropometry criteria for the design of tractor cabs and protection frames. Ergonomics *48*:323-353.

Zhuang Z., Bradtmiller B., **Hsiao H.**, Odencrantz J., Coffey C., Campbell D., Jensen, P., Head-and-Face Anthropometric Survey of U.S. Respirator Users, NIOSH Report, 2007.

Hsiao, H, Whitestone, J, Kau T. [2007]. Evaluation of fall-arrest harness sizing scheme, Human Factors, *49* (3):447-464.

B.3. Expected Impact

This project is expected to have a measurable impact on the safety and health of American firefighters. There are about 1.1 million firefighters driving or riding as passengers on automotive fire apparatus on a daily basis. Implementation of up-to-date firefighter anthropometry in cab, seat, restraint system, egress, and bunker gear design will help reduce firefighter exposure to work-related fatalities associated with "blind spot" crashes, ejection, and extrication as well as injuries associated with slips, falls, and inadequate fit of protective gear. Specifically, this study will fill a critical knowledge gap—the lack of current firefighter anthropometry and work-space data—for the design and manufacturing of fire truck cabs, seats, restraint systems, egresses, and bunker gear.

Responses to this research proposal have been excellent (see Appendices A-E for supporting letters). The NFFF, IAFC, IAFF, FAMA, and NFPA have provided input and expert opinion and consultation to NIOSH for this proposal and have committed to support the research team at all stages of the project. A consortium has been formed for a pilot study of 120 firefighters to be completed in 2008 in order to streamline the data collection and analysis process for the proposed national survey. NFFF, IAFC, and IAFF have committed to aid NIOSH in subject recruitment by contacting national fire stations and facilitating their participation in

the study. FAMA and NFPA will transfer findings of this study into practice by upgrading fire apparatus designs and by updating relevant NFPA standards on fire engine operation and equipment specifications. Because of the strong support, this project is expected to have immediate and long-term effects on reducing firefighter injuries.

B.4. Unique capability of NIOSH in executing the project

The NIOSH anthropometry research team has a combined capability in anthropometry research, 3D scanning technology, cab workspace design, and project management. Since its establishment in 1991, the DSR/PTB anthropometry program has pursued the following three objectives: (1) establish 3D human size and shape database for the design of ergonomically efficient workplaces and occupational tools; (2) develop practical anthropometric guidelines for designers and end-users of industrial equipment; (3) provide critical information for digital human modeling in the research area of traumatic injury prevention. The NIOSH Fatality Assessment and Control Evaluation (FACE) and the Firefighter Fatality Investigation and Prevention programs have provided the team with critical knowledge on risk factors associated with firefighters and automotive fire apparatus. The existing partnerships between NIOSH and state firefighter units will be additional assets to the success of this project, especially in subject recruitment. In fact, this team may be one of the few teams in the nation equipped with the combined skills and capabilities required to successfully accomplish the objectives of this survey project.

C. Preliminary Studies/Progress Report

C.1. Pilot study of firefighter anthropometry

In 2007, NIOSH, NFFF, IAFC, FAMA, NFPA, Wright-Patterson Air Force Base, and Total Contact Inc. jointly initiated a one-year pilot study of U.S. firefighter anthropometric and workspace data. This pilot study aims to accomplish the following objectives: (1) design and construct a fire engine cab buck (Figure 4a), (2) establish procedures for measuring and scanning subjects, and (3) collect preliminary anthropometric data of 120 subjects in preparation for the large scale survey described in this proposal. Subjects were scanned both with and without turnout gear. To accommodate an urgent task on updating specifications for seats and seatbelts, FAMA also used a questionnaire to collect self-reported measurements of some dimensions relevant to seat restraint systems from 15 fire departments, for a total of 737 subjects (682 men and 55 women). The two pilot studies provide us an opportunity to estimate differences in measurements between the “research-team” approach and the “self-report” method for traditional anthropometric measurements, thus determining the need to conduct a large scale controlled study

C.2. Progress report

The construction of a fire engine cab buck has been completed. The procedures for measuring and scanning subjects were also tested. Data collection of 100 (out of 120) subjects was completed in 2007. Figure 3a graphically presents a procedure to quantify the volume required when wearing turnout gear. Figure 3b shows the steps to collect firefighter leg measurements relative to the seat coordinate system; the aggregate of leg dimensions for a population of firefighters can be determined to develop feature envelopes for crewstation design, which will overcome the shortcoming of collecting only traditional anthropometric measurements. Figures 3c, 3d, and 3e shows the anthropometric differences among the 100 sampled subjects (stratified). Even with this small sample, there exists a large variation in body size and proportion as exhibited by the two subjects’ scans (one male and one female) in both seated and standing postures.

As expected, there are some differences between the results from the research-team approach and the self-report method. For instance, the average hip width, sitting dimensions between the two populations were

recorded as almost identical. However, the "research-team" subjects were wearing only shorts while the "self-report" subjects were fully outfitted in clothing and bunker gear. Upon inspection of a "research-team" subject scanned with and without his gear (see Figure 3a), the hip width increases considerably (by 7.3 inches). The pilot study teams are digitizing the hip width for with- and without-gear conditions for the remaining 99 subjects to establish a better estimation of the difference between the two study approaches.

The measurements recorded for the "self-report" population appear to be comparable to the "research team" population for some point-to-point distances but not weight, weight with bunker gear, sitting height with helmet, and hip width. While some of the average measurements differ by a few inches, the differences can possibly be explained by the addition of bunker gear (boots and pants). There are other dimensions that are not comparable or easily explained by scaling factors, as would be expected. In either way, the preliminary study results reaffirm the need to conduct a large scale controlled study to fill the gaps.

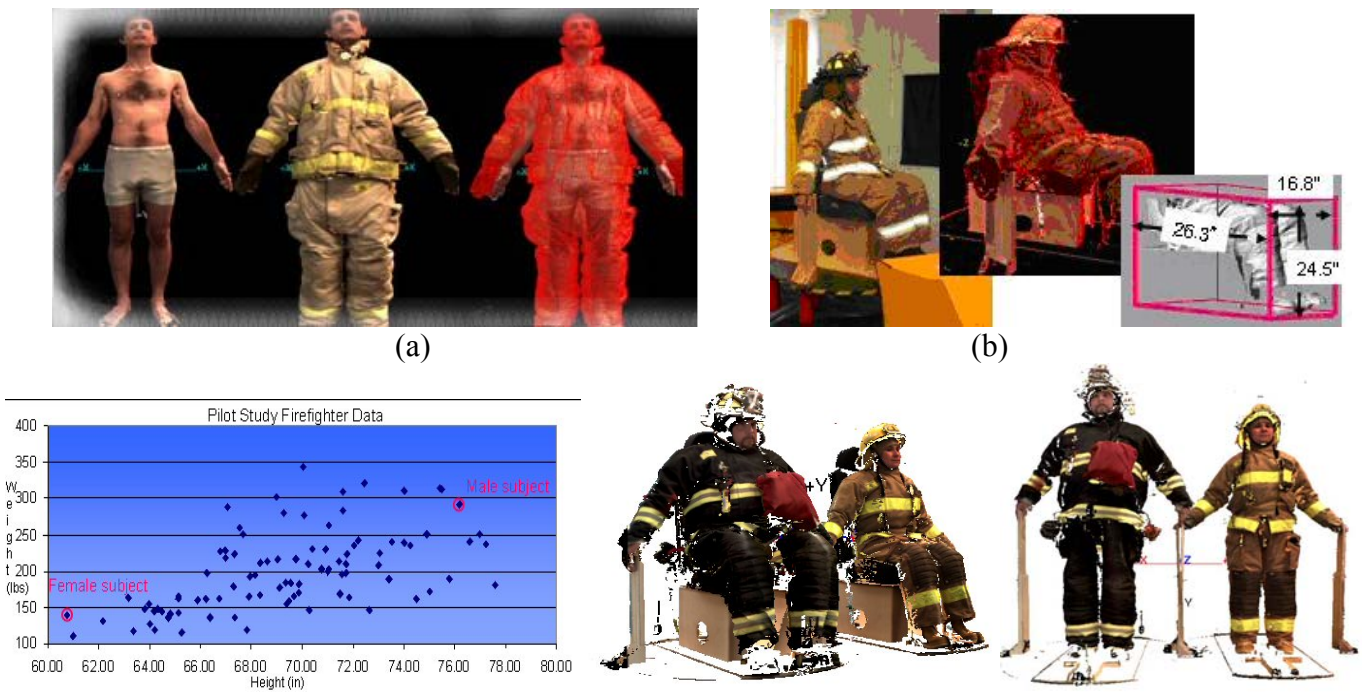


Figure 3. (a) A procedure to quantify the volume required when wearing turnout gear; (b) shown in this figure is the firefighter leg measurements relative to the seat coordinate system; the aggregate of leg dimensions for a population of firefighters can be determined to develop feature envelopes for crewstation design; (c-e) shown in Figure 3c is a bivariate plot of weight versus height measurements of the firefighter pilot study at an interim stage (100 out of 120 subjects). The data includes 71 male and 29 female subjects. Even with this small sample, there exists a large variation in body size and proportion as exhibited by the two subjects' scans (one male and one female) in both seated (Figures 3d) and standing postures (Figure 3e).

D. Design Concept, Hypothesis, Objective/Problem

The proposed project will provide anthropometric data on a representative sample of the U.S. firefighter population for cab, seat, restraint system, egress, and bunker gear design applications.

The project hypothesizes that the current criteria for *seat and egress* as established below in the NFPA 1901 standard do not accommodate 95% of the current firefighters in the US:

(1) Minimum seat cushion width: 460 mm; minimum seat cushion depth: 380 mm; and minimum seating space (horizontal) at the shoulder height: 560 mm;
(2) Minimum back cushion width: 460 mm; minimum back vertical support (460 mm);
(3) Maximum stepping height: 610 mm for the first step and 460 mm for others;
(4) Minimum platform depth: 460 mm; and
(5) Minimum clearance between access handrail and any surface: 52 mm.

This project will also address the following problems associated with *cab, restraint system, and bunker gear* and provide the needed data to establish design criteria for the three mentioned fire apparatus elements:

(1) There is no specification for leg room in the current NFPA 1901. The project will provide firefighter workspace and body measurement data to specify leg room.
(2) NFPA 1901 specifies Type II (3-point) belts for forward facing outboard seating positions, while Type I belts (lap type) are acceptable for all other seats, including tiller cabs. This project will provide updated firefighter anthropometry data to determine the required belt length for both types. In addition, the project will define the belt-length range for each belt component for the design of 4-point and 5-point belts (restraint systems) that would provide enhanced protection to firefighters.
(3) There is no specification for driver eye position, driver-selected seat position, and driver head position for fire engine cab in the current NFPA 1901. The SAE J941, SAE J1517, and SAE J1052 standards have been used respectively as a general guide for these positions for heavy-vehicle design use (SAE 1985a, SAE 1985b, SAE 1987a). This project will provide an adequate firefighter eye range model, a firefighter specific seat position model, and an accurate firefighter head position model for the design of automotive fire apparatuses to optimize driver visibility.
(4) There is no specification for driver shin-knee position for clutch and accelerator and driver stomach position for driving wheel arrangement in the current NFPA 1901. The SAE J1521 standard (SAE 1987b) and SAE J1522 standard (SAE 1985c) are not representative of the firefighter shin-knee position range and stomach position for 95% of the current firefighter population in the U.S. The project will provide a firefighter shin-knee model for the arrangement of clutch and accelerator as well as a firefighter stomach model for the arrangement of driving wheel, seat, and cab space.

E. Study Design and Methods

E.1. Sampling Plan

This survey will use a stratified sampling plan (3-age x 3-race/ethnicity × 2-gender combinations) to collect anthropometric data across the U.S. Based on the U.S. Fire Department Profile Through 2005, of the 1,136,650 firefighters, the under-30-age group (age 16-29) accounted for 287,450 (or 25.3% of all firefighters). The 30-39 age group accounted for 330,400 (29.1%); the 40-49 age group accounted for 296,450 (26.1%); and the above 50 age group accounted for 222,350 (19.5%) (Karter 2006). For this proposed study, the data can be reorganized into 3 groups (excluding under age 18) with an equal population distribution: 365,845 firefighters (32.8%) for age 18-32, 379,505 (34%) for age 33-44, and 370,575 (33.2%) for age 45-65, with a total of 1,115,925 firefighters. As to the gender and ethnicity issues, Department of Labor Household Data Survey of 2000-2004 indicated a distribution of 4.2% women, 9.3% Black (male), 7.3% Hispanic-origin (male), and 79.2% White (male) firefighters (BLS 2006). Since female firefighters are relatively few in number, it is impractical to further divide them into different racial/ethnic groups. So, the total cells that can be arranged for the study to compare anthropometric differences among national firefighters are 12 (Table 1).

The needed within-cell sample size can be calculated using the following equation: $\left|\overline{X}-\upsilon\right| = \frac{\delta * \sigma}{\sqrt{n}}$, where $\left|\overline{X}-\upsilon\right|$ is within-cell accuracy, $\overline{X}$ the sample mean of the subgroup, υ the true mean of the subgroup, n the sample size, σ the standard deviation of the subgroup, and δ the eccentricity (1.96 for 5% two-sided probability). Based on the standard deviation of stature from the CAESAR-US database (79 mm for men and 73 for women) and the desired cell accuracy of 18 mm for this study, the estimated sample size is 74 for males and 64 for females. Namely, at a 95% confidence level the sample sizes of 74 and 64 would have sufficient power for the sample mean to be within 18 mm of the true mean of the subgroup. Therefore, 75 subjects per cell are proposed. The "all other races/ethnicity" group is merged with the Hispanic group because its percentage is too small to be an independent racial/ethnic group and its racial diversity matches that of the Hispanic group.

It should be noted that stature would give us the most conservative estimate and the level of 18 mm cell accuracy is deemed acceptable for this type of survey study. It is also worth mentioning that the overall national margin of error will of course be much smaller than the within-cell margin; the estimated margin of error with a sample size of 75 in each cell would be approximately 5 mm which is within the measurement error range. It is doubtful that a better margin of error is necessary or cost justified. Table 1 shows that a national sample size of 900 subjects would provide sufficient information for between-gender, between-races/ethnicity, and between-age comparisons.

Table 1. Targeted Number of Subjects

Age Groups	Male			Female
	Non-Hispanic White	Non-Hispanic Black	Hispanic and All Other Races/ Ethnicity	All Races/ Ethnicity
18-32	75	75	75	75
33-44	75	75	75	75
45-65	75	75	75	75
Total	900			

In practical applications of anthropometry for product design, the proportions of gender, races/ethnicity, and age populations need to be further considered and adjusted accordingly. The Department of Labor Household Data Survey of 2000-2004 indicated a distribution of 4.2% women, 9.3% Black (male), 7.3% Hispanic-origin (male), and 79.2% White (male) firefighters (NFPA 2006b). In this regard, 712 white, 84 black, 66 Hispanic, and 38 female firefighters would be expected if a random national sampling of 900 firefighters is performed. In order to maintain the power to evaluate the anthropometric difference among the different ethnicity and gender groups of firefighters, a minimum of 75 subjects should be kept in each group. In addition, an over-sampling of female firefighters would be necessary to address some fire apparatus design issues (such as bunker-gear fit, fire engine operation, and seat adjustment) that are unique to females. Therefore, a 70%, 10%, 10%, and 10% sample plan is proposed which corresponds to having 630 white males, 90 black males, 90 Hispanic males, and 90 females. Table 2 presents the estimated number of subjects in each stratum. In this design, the lowest cell accuracy for stature (Non-Hispanic Black × Age and Hispanic × Age) is 28 mm whereas the highest cell accuracy (White × Age) is 11 mm. The cell accuracy is 26 mm for Female x Age subgroups and the lowest ethnicity group accuracy is 15 mm.

Table 2. Estimated Number of Subjects

Age Groups	Male						Female	
	Non-Hispanic White		Non-Hispanic Black		Hispanic and All Other Races/ Ethnicity		Count	Percent
	Count	Percent	Count	Percent	Count	Percent		
18-32	210	23.3	30	3.3	30	3.3	30	3.3
33-44	210	23.3	30	3.3	30	3.3	30	3.3
45-65	210	23.3	30	3.3	30	3.3	30	3.3
Total	630	70	90	10	90	10	90	10
Grand Total	Count =900				Percentage = 100			

To collect data nationwide, the continental United States will be divided into four regions as shown in Table 3. The number of subjects in each region is modified by the size of population in that region in the 2000 U.S. Census (U.S. Census Bureau 2001). This modification is based on the assumption that the number of firefighters is proportional to the size of the population it serves.

Table 3. Data Collection Regions and Sample Size

Region	Data Collection Site	States Represented	U.S. Total (%)	Sample Size
I. Pacific West	Phoenix, AZ	WA, OR, ID, MT, WY, CA, NV, AZ, CO, UT, NM	21.95	198
II. North Central	Chicago, IL	MN, IA, MO, ND, SD, NE, KS, WI, IL, MI, IN, OH, KY	24.48	220
III. North East	Baltimore, MD	ME, NH, VT, MA, RI, CT, NY, NJ, PA, DE, MD, WV, VA, DC	24.72	222
IV. South	Dallas, TX	TN, NC, SC, GA, FL, AL, MS, TX, OK, AR, LA	28.85	260
Total			100	900

Table 4 shows the sampling plan adjusted by firefighter population density in each region. This table is based on the assumption that all racial/ethnic populations are distributed equally across the four regions, which certainly is not realistic. Further adjustments are done in Table 5 to reflect region-by-ethnicity distributions of firefighters.

Table 4. Sampling Plan with Equal Racial/Ethnic Distribution across the Four Regions

Data Collection Site	Male									Female			Total
	White			Black			Hispanic/Other						
	18-32	33-44	45-65	18-32	33-44	45-65	18-32	33-44	45-65	18-32	33-44	45-65	
Phoenix, AZ	45	45	45	7	7	7	7	7	7	7	7	7	198
Chicago, IL	52	52	52	7	7	7	7	7	7	7	7	7	219
Baltimore, MD	53	53	53	7	7	7	7	7	7	7	7	7	222
Dallas, TX	60	60	60	9	9	9	9	9	9	9	9	9	261
Total	630			90			90			90			900

Table 5. Final Sampling Plan

Data Collection Site	Male									Female			Total
	White			Black			Hispanic/Other						
	18-32	33-44	45-65	18-32	33-44	45-65	18-32	33-44	45-65	18-32	33-44	45-65	
Phoenix, AZ	45	45	45	3	3	3	13	13	13	7	7	7	204
Chicago, IL	52	52	52	6	6	6	3	3	3	7	7	7	204
Baltimore, MD	53	53	53	8	8	8	5	5	5	7	7	7	219
Dallas, TX	60	60	60	13	13	13	9	9	9	9	9	9	273
Total	630			90			90			90			900

The final sampling plan (Table 5) takes into account the geographic density of racial/ethnic distributions calculated from U.S. Census 2000. The highest percentage of black Americans live in the South region (44%), with the North East, North Central/Great Lakes, and Pacific West regions accounting for 27.5%, 19.6%, and 8.8% of the total black American population, respectively. For the Hispanics, 43% live in the Pacific West, with 31%, 16.8% and 9.1% in the South, North East, and North Central/Great Lakes regions, respectively. As a result of the geographic distributions of both racial/ethnic groups, the number of subjects in each cell is adjusted accordingly. Whites and females are not further adjusted from Table 4.

The final sampling plan of 900 subjects (Table 5) will be used in the study to collect traditional anthropometry data (thereafter refer as Part I study). A half of all males will be selected for 3D scanning and workspace evaluation. Therefore, 315 White, 45 Black, and 45 Hispanic males will participate in the 3D scanning and workspace evaluation study (Part II study). All 90 females will also participate in Part II study; this over-sampling of female firefighters is necessary to address some fire apparatus design issues (such as bunker-gear fit, fire engine operation, and seat adjustment) that are unique to females. Since the 495 subjects in Part II study are "sequentially sampled" from Part I study, they are expected to be as representative of the U.S. firefighter population as those from Part I study.

E.2. Subject Recruitment

Subjects will be approached through firefighter associations and be arranged in small groups to participate in the study at 4 data collection sites as identified above. NFFF, IAFC, and IAFF have committed to provide assistance in subject recruitment by mobilizing their network. Because NFFF, IAFC, and IAFF have excellent networking capabilities, it is expected that subject recruitment will be a straightforward process.

E.3. Materials

E.3. 1. Cab Buck

NIOSH has constructed a truck cab buck for this project (Figure 4a). This buck consists of a windshield, door (driver's side), floor, seat, seat belt, steering wheel, accelerator, brake, and clutch. The buck has no hood to simulate the cab-over style fire apparatus (Figure 4b). The adjustable parts of the cab are the driver's seat (up-down, fore-aft, recline), seat back angle, steering wheel (telescoping, translating and tilting), and brake pedal (fore-aft). The unique feature of the cab is that its dimensions are generic, non-specific to particular models of fire-truck cab, and the seat and steering wheel are adjustable over a wide range so that the cab is capable of accommodating all participants. The cab adjustment values are presented

in Figure 4c. Negative values indicate a position forward of the Accelerator Heel Point (AHP). No minimum and maximum telescope values are specified because the reference point for telescope is arbitrary.

	Min	Max	Range
Seat			
Back Angle, Degrees	13.5	18.0	4.5
H point – AHP (fore-aft), mm	305	855	550
H point – Floor (up-down), mm	250	885	635
Steering wheel			
Size (diameter), mm	457	457	0
Steering column angle, degrees	50	75	25
Telescope, mm	--	–	405
Steering Pivot longitudinal travel, mm	0	-365	365
Brake -AHP (fore-aft), mm	0	-387	387

(a) (b) (c)

Figure 4. The cab buck for the proposed study consists of windshield, door, seat, steering wheel, accelerator, brake, and clutch (a), which simulates the cab-over style fire apparatus (b). The cab adjustment values are described in (c).

E.3.2. Field Laboratory

NIOSH will acquire a rental space to house the truck cab buck, a Cyberware whole body laser scanner, a head scanner, a hand scanner, a Platinum 8-foot FaroArm, and a measurement area for traditional anthropometry. Please see **Major Equipment** subsection under 4. **RESOURCES** section and Figure 1 for details. The research team will make an effort to select a space near a major fire department in each of the 4 selection areas: Baltimore, MD, Phoenix, AZ, Chicago, IL, and Dallas, TX.

E.3.3. Training Manual for Anthropometric and Workspace Measurement

A training manual will be prepared to describe in detail how the anthropometric and workspace measurements are to be obtained, including body posture and position requirements, landmark identification, measurement procedures as well as cab workspace dimensions. This manual will be used to train the measurement team members how to take valid and accurate measurements.

E.4. Work Space Test Setting

As described in E.3. 1 Cab Buck section, seat height, seat fore-aft position, seat-back angle, and steering wheel angle will be adjustable to the subjects. The initial positions of these work space parameters will be randomly set at three different values: (1) seat heights from the floor: low (300 mm), mid (550mm), and high (800 mm), (2) seat fore-aft positions from AHP: fore (360 mm), mid (580 mm), and after (800 mm), (3) back angle: 14°, 16°, 18° from vertical, and (4) steering wheel angle: 55°, 65°, and 75° from vertical. The steering wheel size will be 457 mm, which is the most common steering wheel size in modern fire-truck cabs. The steering wheel column will be set at the middle of its longitudinal travel range. The gas pedal and clutch will be fixed while the brake pedal will be operable.

E.5. Body Landmarks, Anthropometric Measures and Workspace Values

E.5.1. Body Landmarks

The following 56 body landmarks will be used to define anthropometric measurements in the survey. The definitions of these dimensions can be found in Hsiao et al. (2005), Blackwell et al. (2001), and Gordon et al. (1989): (1) Abdominal point, anterior, (2) Acromion, left and right, (3) Acropodion, left and right, (4) Buttock point, posterior, (5) Dactylion II, right, (6) Dactylion III, right, (7) Ecotocanthus, (8) Fifth metatarsophalangeal protrusion, (9) First metatarsophalangeal protrusion, (10) Forearm point lateral, (11)

Hip point, (12) Knee point, anterior, left and right, (13) Lateral femoral epicondyle, left and right, (14) Lateral malleolus, right, (15) Metacarpale II, (16) Metacarpale III, (17) Metacarpale V, (18) Olecranon, bottom and rear, (19) Popliteal fossa, (20) Posterior Calcaneous, (21) Radial Styloid, (22) Thigh point, top, (23) Thumb protrusion, right, (24) Trochanter, (25) Vertex (top of the head), (26) Back of head, (27) Cervicale (C7), (28) L4, (29) Posterior superior iliac spine, left and right, (30) Pupil, right and left, (31) Suprapatella, (32) Thelion/bustpoint, left and right, (33) Tragion, left and right, (34) Ulna Stylion, (35) Anterior superior iliac spine (ASIS), left and right, (36) Axilla point, anterior, left and right, (37) Axilla point, posterior, left and right, (38) Suprasternale, (39) T10, (40) Neck Base, Trapezius point, left and right, (41) Biceps point, right, (42) Calf point, left and right, (43) Clavicle point, left and right, (44) Glabella, (45) Gonian, left and right, (46) Illiocristale, left and right, (47) Infraorbitale, left and right, (48) Lateral humeral epicondyle, left and right, (49) Menton, (50) Midshoulder, (51) Promenton, (52) Sellion, (53) Thumbtip, left and right, (54) Waist (omphalion) left and right; anterior and posterior, (55) Waist (natural indentation) left, right, anterior and posterior, and (56) Substernale.

E.5.2. Anthropometric measurements.

The following 88 measures will be taken on each subject by traditional anthropometry techniques. Definitions of these dimensions are available in Stirling (2006), Hsiao et al. (2005), Blackwell et al. (2001), and Gordon et al. (1989).

Sitting posture: (1) Abdominal Extension Depth, (2) Abdominal Extension Height, (3) Acromial (Shoulder) Height, (4) Bideltoid Breadth, (5) Buttock-Knee Length, (6) Buttock-Popliteal Length, (7) Elbow Rest Height, (8) Eye Height, (9) Hip Breadth, (10) Knee Height, (11) Knee Breadth, (12) Overhead Fingertip Reach, (13) Popliteal Height, (14) Shoulder-Elbow Length, (15) Sitting Height, (16) Thigh Clearance, (17) Lateral Femoral Epicondyle - Lateral Malleolus Length, (18) Trochanter-Lateral Femoral Epicondyle Length, (19) Functional Leg Length, (20) Forearm-Hand Length, (21) Functional Grip Reach, (22) Arm Length (Shoulder-Wrist), (23) Bi-Acromial Breadth, (24) Overhead Grip Reach, (25) Thumbtip Reach, (26) Upperarm Circumference (biceps Circumference), Flexed, and (27) Forearm Circumference, Flexed.

Standing posture: (28) Stature, (29) Weight, (30) Cervical Height (C7), (31) Acromial Height, (32) Axilla (Armpit) Height, (33) Trochanterion Height, (34) Acromion To Grip Length, (35) Crotch Height, (36) Overhead Grip Reach, (37) Knee Height, (38) Waist Back Height, (39) Waist Height, (40) Chest Breadth, (41) Bust Point To Bust Point, (42) Chest Depth, (43) Waist Breadth, Omphalion, (44) Waist Depth, (45) Virtical Trunk Circumference, (46) Functional Arm Span, (47) Midshoulder To Bust Point, (48) Bust Point To Trochanter, (49) Midshoulder To Center Of Bust Points, (50) Center Of Bust Points To Left Trochanter, (51) Suprasternale To Substernale, (52) Midshoulder To Center Of Shoulder Blades, (53) Center Of Shoulder Blades To Left Trochanter, (54) Gluteal Furrow Arc, (55) Gluteal Furrow Point To Gluteal Furrow Point, (56) Neck Circumference, (57) Chest Circumference, (58) Waist Circumference, (59) Hip Circumference, (60) Calf Circumference, and (61) Thigh Circumference.

Head and Hands: (62) Head Length – Chin To Vertex, (63) Head Length – Front To Back, (64) Head Breadth, (65) Head Circumference, (66) Interpupillary Distance, (67) Jaw Width, (68) Face Breadth, (69) Bitagion Arc Length, (70) Bitagion Arc Length, (71) Face Length – Menton To Brow Ridge, (72) Face Length – Menton To Naison, (73) Hand Length, (74) Palm Length, (75) Hand Breadth Across Thumb, (76) Hand Breadth, (77) Palm Thickness, (78) Hand Thickness Max, (79) Thumb Length, (80) Thumb Width, (81) Finger Length – Middle Finger, (82) Finger Width – Middle Finger, (83) Grip Strength, (84) Foot Breadth, Horizontal, (85) Foot Length, (86) Lateral Malleolus Height, (87) Shoe Length, Exterior, and (88) Shoe Width, Exterior.

E.5.3. Cab Buck Workspace Values.

The following 20 sets of cab accommodation values (coordinates) will be collected with a FaroArm: (1) eye position, right and left; (2) elbow position, right and left; (3) foot reach on clutch; (4) forward reach positions, left and right; (5) hand position on the steering wheel, left and right; (6) head position, top; (7) knee position, left foot on clutch; (8) knee position, right foot on accelerator; (9) knee position, right foot on brake (10) pelvis position, left and right; (11) shoulder position, right and left; (12) trochanter right and left, cervical, suprasternale and substernale positions; (13) Preferred brake depressing depth and angle; (14) seat fore-aft travel; (15) seat height; (16) seat back angle; (17) steering wheel center position and angle; (18) Safety belt anchorage position and length; (19) Stomach-steering wheel clearance, and (20) Thigh-steering wheel clearance. All measured values in the buck are referenced to the accelerator heel point (AHP). For definitions of these values, please see Sanders and Shaw (1985).

E.6. Procedures

E.6.1. Traditional Measurement Assignment

Upon arriving at the field laboratory, the subject will view a PowerPoint ™ presentation, which describes the study and the tasks the subject is to perform. If he/she agrees to participate, the subject will sign a consent form and fill out a short demographic sketch form. The subject will then be taken to a dressing room, where he/she changes clothing – bike shorts for men and bike shorts and halter top for women.

For traditional anthropometry, the subject will first assume a standing posture and then a sitting posture. For the standing posture, the subject will stand erect with heels lined up with pre-marked footprints on the floor and hands resting naturally by each side. He/she will be told to face forward with equal weight on both feet. For the sitting posture, the subject will sit erect on a specially designed bench with the head facing forward. The shoulders and upper arms are relaxed, and the forearms and hands are extended forward horizontally with the palms facing each other. The thighs are parallel and the knees are flexed 90 degrees with the feet in line with the thighs. During the two postures, an investigator will locate 56 landmarks on the subject's skin, by gently feeling for specific bones and joints; female firefighters will be handled by female investigators. The landmarks will then be marked with a non-permanent cosmetic marker. Markers will be placed on the clothing overlying the actual landmarks if landmarks are covered by the clothing. After landmarking, the investigator will measure 88 body dimensions at the standing and sitting postures. All 900 subjects will participant in this part. Four hundreds and ninety-five (495) of the 900 subjects will continue to complete procedures E.6.2, E.6.3, and E.6.4 below.

E.6.2. Standing and Seated Scan Assignment

Following the data collection using traditional anthropometry, the landmarks will be covered with reflective markers and a form-fitting cap will be placed on the head to cover the hair. The subject then takes the whole body scans. The subject will be scanned in 6 posture-by-dress combinations: standing with bike short, sitting with bike short, standing with protective clothing, sitting with protective clothing, standing with protective clothing and SCBA, and sitting with protective clothing and SCBA (Figures 5 a-f)

- Standing posture (Figures 5a, 5c, and 5e). For this scan, the subject will line up the feet with the pre-marked footprints on the scanner platform. The subject's arms will be 20 cm away from the torso with palms facing slightly forward, and the two legs will be about 10 cm apart at heels with toes about 30 degrees away from the sagittal plane. The subject will be instructed to hold his/her breath for 17 seconds during each scanning.
- Sitting Posture (Figures 5b, 5d, and 5f). For this scan, a specially made stool, adjustable in height, will be placed on the scanning platform. The subject will be seated on the stool, torso kept erect, eyes

looking straight ahead, knees kept at 90 degrees, two legs about 10 cm apart, elbows kept at 90 degrees, palms facing each other, and fingers extended and pointing forward. The subject will be instructed to stay still and hold his/her breath while the 17-second scanning is completed.

(a) (b) (c) (d) (e) (f)

Figure 5. Six scans will be conducted after traditional anthropometry measurement: (a) standing with bike short, (b) sitting with bike short, (c) standing with protective clothing, (d) sitting with protective clothing, (e) standing with protective clothing and SCBA, and (f) sitting with protective clothing and SCBA. Reflective markers are not shown in these demonstrative photos.

E.6.3. Cab Configuration Assignment

After completing the 6 scans, the subject will be taken to the truck buck for workspace measurement with protective clothing. Before the subject enters the cab buck, the investigator will make sure that all the adjustable parts of the buck are randomly set at the high, median, or low values as specified in E.4. Work Space Test Setting section. The subject will then sit in the driver's seat. The subject, with investigators' assistance, will make adjustments in seat position (seat height, fore-aft travel, and back angle) as well as steering wheel telescoping, fore-aft travel, and tilting position. The sequence of the adjustment will be seat height, seat fore-aft position, seat back angle, steering wheel tilting, and steering wheel position. After he/she is satisfied with all adjustments, the subject will then be instructed to fasten the seat belt. Then, the subject will be instructed to sit in a comfortable driving posture, with both hands holding the steering wheel, left foot (ball) resting on clutch, and right foot resting on the accelerator. A final adjustment will be allowed. The values of seat and steering positions will be recorded automatically and the seat belt length will be recorded manually. The investigator will then take workspace measurements using the FaroArm. For top of the head (vertex) and eye position measurements, a head clamp will be used to fix head position. The head clamp will then be loosened and moved out of the way for other cab measurements. Next, the right knee position will be registered while the foot is on the accelerator. The subject will then place the ball of his/her left foot on the clutch without pointing the toes. The position of the clutch relative to the AHP will be recorded. For hand grip reach measurement, the subject will be instructed to reach for the knobs located to the front of the cab buck using three-finger grip hand posture. The subject will be asked to reach for two knobs with the left hand and two knobs with the right hand. The subject will be instructed to lean slightly forward and reach toward the knob, stopping at a comfortable position. The position of the thumb tip will be recorded. After these measurements are taken, relevant work-space dimensions (i.e., stomach-steering wheel clearance, hand position on the steering wheel, and thigh-steering wheel clearance) will be measured.

6.4. Seated Driving Scan Assignment. After the workspace data collection, a truck seat will be placed on the whole body scanner platform. The spatial layout of the seat, clutch, accelerator, and steering wheel will

follow those obtained during the subject's cab workspace measurement (Figure 6a). While an investigator is working on the truck-seat arrangement, a head scan and a right-hand scan will be performed (Figures 6b and 6c). After head and hand scanning, the subject will move to the whole body scan area for the seated driving scan (Figure 6d). Physical objects (accelerator, clutch, and steering wheel) will be used to make sure that the posture closely mimics his/her posture during the cab workspace measurement. For this scan, the subject will be seated comfortably with protective clothing with hands holding onto a steering wheel, eyes looking straight ahead, the left foot (ball) resting on the clutch pedal, and the right foot resting on an accelerator pedal. The subject will be instructed to sit still and hold his/her breath while the 17-second scanning is completed. After the scanning is completed, the subject will change back into street clothes, will be compensated for his/her travel cost, and will then be dismissed.

(a) (b) (c) (d)

Figure 6. (a) Truck-seat arrangement, (b) head scan, and (c) hand scan will be performed before (d) the whole body scan of the seated driving posture with protective clothing. Reflective markers are not shown in these demonstrative photos.

E.7. Data Analysis

E.7.1. Data summary and tabulation

All 88 traditional anthropometric measurements will be summarized for comparisons with those in the literature. For each measurement, the following summary statistics will be provided: percentiles, mean, standard deviation, minimum and maximum. All 20 sets of cab workspace measurements will be tabulated and made available to project partners to use in fire-engine cab designs.

E.7.2. 3D laser scan database

An electronic database will be established to include 3D scans of all 495 subjects in seven posture-by-dress combinations (3,465 scans). All the scans will be stored in the polygon file format (PLY), a popular 3D graphic format, accompanied by corresponding landmark files. The scans will be made available to project partners for equipment design purposes.

E.7.3. Digital human models and apparatus design

Multivariate-based cab and seat accommodation models. This project will develop a multivariate cab and seat accommodation model, using the Multivariate Anthropometric Method (MAM). This method generates a number of principal component factors (Hsiao et al., 2005) based on anthropometric data of the 900 participating firefighters. These principal components will be used to develop an "ellipsoid" which includes data of dimensions of 95% of the U.S. firefighter population. Data points along the surface of the ellipsoid plus the centroid point will be selected to form a 15-man model (Figure 7a). For each data point, an individual subject from the 495 scanned subject pool with his/her body dimensions closest to each of the 15 models will be selected to "represent" the firefighter population. This model will consist of all individuals

representing distinct body types and dimensions that must be accommodated by an ergonomically efficient fire truck cab. These 15 body types will be available to automotive fire apparatus manufacturers and digital human modeling developers to import into digital modeling programs for cab design purposes.

In addition, to evaluate and update the existing standards related to the cab occupant and environment, this project will also develop models for the firefighters' head, eye, knee, hand and other landmarks at the seat position (Figure 7b). Body landmark coordinates from the 495 scanned subjects will be used. Principal component analysis of landmark coordinates reveals the geometric description of a multivariate normal distribution of a multivariate normal ellipsoid of constant density. This ellipsoid approximates the distribution of the landmark point cloud. The mean values for each coordinate define the center of the ellipsoid and the origin for a new axis system. Geometrically, the three new axes, represented by the three components, are formed by rotating from the original landmark coordinates about their means. The major axis of the ellipsoid, represented by the first component, provides the best possible fit to the data points (as measured to have the minimum sum of the squared perpendicular distances from the data point to the new axis). The 1st minor axis of the ellipsoid, represented by the second component, has the minimum projected distances of the points in a direction orthogonal to the first component. The 2nd minor axis of the ellipsoid, represented by the third component, has the minimum projected distances of the points in a direction orthogonal to both the first and the second component. The elements of the eigenvectors of the landmark coordinate covariance matrix are the direction cosines of the new axes related to the old. The semi-axis length of the new axis is proportional to the square root of each corresponding eigenvalue of the landmark coordinate covariance matrix and can be calculated by the following equations:

Semi-axis lengths of ellipsoid $= c\sqrt{\lambda_i}$

Axes of the ellipsoid $= \pm c\sqrt{\lambda_i}\ e_i$ Where $\sum e_i = \lambda_i, e_i \quad i = 1,2,3$

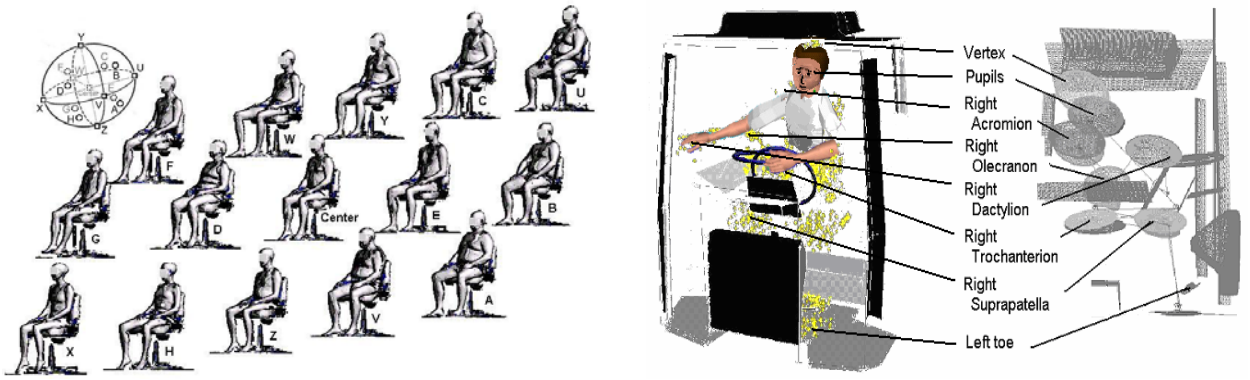
$\sum$ is the covariance matrix of the landmark data.

λ_i is the eigenvalue of the covariance matrix $\sum$.

e_i is the eigenvector of the covariance matrix $\sum$ associated with eigenvalue λ_i and has unit length.

$c^2 = \chi_3^2(\alpha)$, where $\chi_3^2(\alpha)$ is the upper (100 α)th percentile of a chi-square distribution with three degrees of freedom.

Ellipsoids of equal concentrations with (1-α)100% probability can be described by choosing $c^2 = \chi_3^2(\alpha)$. Theoretically, the probability that any landmark in the distribution falls within a 95% probability ellipsoid is 95% (Johnson and Wichern 1988). The multivariate cab space and landmark models provide more adequate information for cab design and standard updates than current univariate approaches.

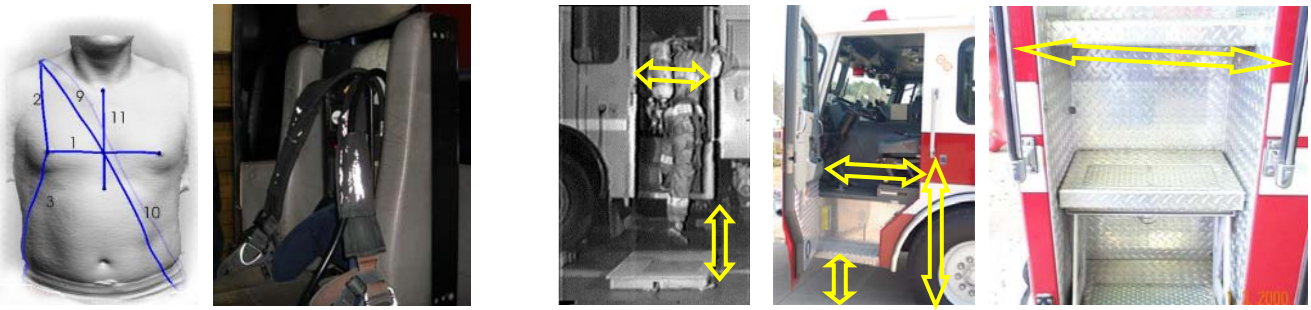


(a) (b)

Figure 7. (a) An example of representative body models based on a "principal component analysis" and (b) the feature envelopes of subjects' head, eye, and other landmarks during the comfortable seated driving.

Seatbelt accommodation models. Right-mid-shoulder-to-right-bust-point distance, right-mid-shoulder-to-center-of-bust-points distance, right-mid-shoulder-to-left-trochanter distance (functional measurements for shoulder strap length), waist circumference, right-to-left-posterior-superior-iliac-spine curve (correlated to waist strap length) data will be analyzed using the Principal Component Analysis (PCA) approach to define seatbelt component adjustment ranges for the current 3-point seatbelts and advanced 4-point and 5-point restraint systems (Figures 8a and 8b). In addition, seat belt length data collected from the workspace study will be analyzed, using univariate statistics, to determine the minimum length requirement for current lap belts (2-point belts).

Egress/ingress accommodation models and egress/ingress dimension specifications. Forearm-to-forearm breadth and hip width while wearing bunker gear will be analyzed, using univariate statistics (Hsiao and Halperin, 1998), to determine the minimum requirement for egress/ingress width. Leg length, stepping height, foot breadth, foot length, hip width, and forearm-to-forearm breadth will be evaluated, using multivariate anthropometric method (MAM) to define overall egress configurations.



(a) (b) (c) (d) (e)

Figure 8. Data corresponding to strap lengths will be extracted from 3D scans (8a) and will be analyzed using the Principal Component Analysis approach to define seatbelt component adjustment ranges for the current 3-point seatbelts and advanced 4-point and 5-point restraint systems (8b). Leg length, stepping height, foot breadth, foot length, hip width, and forearm-to-forearm breadth (8c) will be evaluated, using multivariate anthropometric method to define overall egress configurations (8d, 8e).

Bunker gear accommodation models. The maximum breadth (side-to-side distance), depth (front-to-back distance), and height (top-to-bottom distance) of the upper-torso volume space and the lower-torso volume space (also known as "torso bounding boxes") will be extracted from 3D scan images (Hsiao et al., 2007). The 10th rib landmarks will be used to separate the torso images into the upper and lower torso regions. These dimensions will be used to explore the interaction of the general body shape and dimensions with current bunker gear fit (Figure 9a and Figure 3). A multinomial logistic regression with forward selection will be used to search for the most influential factors (i.e. independent variables) that determine bunker gear sizes (McFadden 1974). The dependent variable is the best-fitting size of the bunker gear; and potential independent variables include gender, height, weight, and the torso bounding-box parameters.

In addition, torso shape and size will be digitized and analyzed, using the Elliptic Fourier Analysis (EFA) approach, to determine the adjustment range of SCBA strap (Figure 9b). The anthropometric dimensions include right-mid-shoulder-to-left-trochanter distance, bust-point-to-bust point, right-mid-shoulder-to-center-of-bust-points distance, right-bust-point-to-right-trochanter distance, and right-mid-shoulder-to-center-of-shoulder blade (back strap). The EFA approach is based on the work of Kuhl and Giardina (1980) and has been successfully used in evaluating fall-arrest-harness sizing systems and in determining harness component adjustment ranges (Hsiao 2004). The torso contour can be described by a series of constants and coefficients. The constants are defined as:

$x(t) = A_0 + \sum_{n=1}^{N} a_n \cos nt + \sum_{n=1}^{N} b_n \sin nt$, $y(t) = C_0 + \sum_{n=1}^{N} c_n \cos nt + \sum_{n=1}^{N} d_n \sin nt$, and

$z(t) = E_0 + \sum_{n=1}^{N} e_n \cos nt + \sum_{n=1}^{N} f_n \sin nt$, where n is the harmonic number, N is the maximum number of harmonics and the variable t is over the range 0 to 2π.

The elliptic Fourier coefficients are defined as:

$$a_n = \frac{1}{n^2\pi}\sum_{p=1}^{q}\frac{\Delta x_p}{\Delta t_p}\left[\cos(nt_p) - \cos(nt_{p-1})\right],\ b_n = \frac{1}{n^2\pi}\sum_{p=1}^{q}\frac{\Delta x_p}{\Delta t_p}\left[\sin(nt_p) - \sin(nt_{p-1})\right]$$

for the x projection,

$$c_n = \frac{1}{n^2\pi}\sum_{p=1}^{q}\frac{\Delta y_p}{\Delta t_p}\left[\cos(nt_p) - \cos(nt_{p-1})\right],\ d_n = \frac{1}{n^2\pi}\sum_{p=1}^{q}\frac{\Delta y_p}{\Delta t_p}\left[\sin(nt_p) - \sin(nt_{p-1})\right]$$

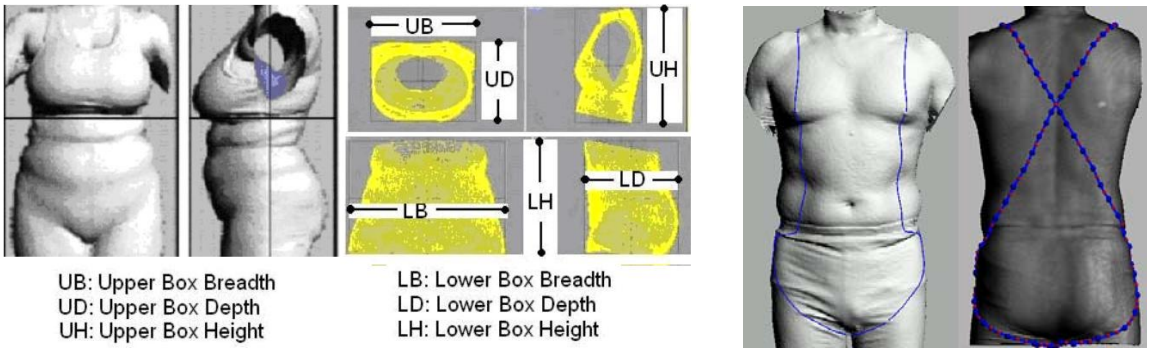
for the y projection,

$$e_n = \frac{1}{n^2\pi}\sum_{p=1}^{q}\frac{\Delta z_p}{\Delta t_p}\left[\cos(nt_p) - \cos(nt_{p-1})\right],\ f_n = \frac{1}{n^2\pi}\sum_{p=1}^{q}\frac{\Delta z_p}{\Delta t_p}\left[\sin(nt_p) - \sin(nt_{p-1})\right]$$

for the z projection,

where q is the number of points in the outline, Δt_p is the distance between point p and p+1 along the outline, and Δx_p, Δy_p, and Δz_p are the x, y, and z components of the line segment from p-1 to p.

A U.S. firefighter anthropometric and workspace source book will be compiled based on the sources of data mentioned in sections E.7.1., E.7.2. and E.7.3.



(a) (b)

Figure 9. (a) A torso bounding box approach and (b) an Elliptic Fourier Analysis (EFA) approach for determining bunker gear fit and the adjustment range of SCBA strap.

E.7.4. Evaluating the current NFPA standards on firefighter apparatus

The anthropometric data and digital human models developed in this study will also be used to update NFPA1901 standards on firefighter physical dimensions for cab, seat, seatbelt, egress, and bunker gear design applications. The cab accommodation models, developed in this study, will be compared with those used in the SAE standards on truck driver eye, head, shin-knee, stomach, and selected seat positions. The purpose of these comparisons is to evaluate the validity of the existing standards for fire apparatus, which were adopted from those for general heavy vehicles. The SAE standards to be evaluated are: J941 OCT85 – Motor Vehicle Driver's Eye Range; J1517 Oct85 – Driver Selected Seat Position; J1052 May87 – Motor Vehicle Driver and Passenger Head Position; J1521 – Truck Driver Shin-Knee Position for Clutch and Accelerator; J1522 OCT85 – Truck Driver Stomach Position. Results from this analysis will serve as quantitative justification for developing firefighter-based workspace criteria for the NFPA 1901 standards.

F.) Human Subjects, OMB, and Staff Health and Safety

F.1. Gender and Minority Inclusion for Research Involving Human Subjects.

The study sample will include 10% female firefighters, 10% African American male firefighters, 10% male firefighters from the Hispanic and all other racial and ethnic groups, and 70% White male firefighters. This gender and race/ethnicity mix is determined based on the Department of Labor Household Data Survey of 2000-2004 and U.S. Census 2000 (NFPA 2006) with an oversampling for females, African American males, and Hispanic males as explained in the ***E.1. Sampling Plan*** section.

NIOSH are working closely with NFFF, IAFC, IAFF, and NFPA on how to reach out to women and minority firefighters in the study process. NFFF and IAFC are committed to contact fire stations to identify individual female and minority firefighters. Because of the excellent networking capability of the NFFF, IAFC, IAFF, and NFPA, it is expected that this process will be straightforward.

F.2. Protection of Human Subjects.

This survey project is qualified for an expedited human subject review because the study involves only non-invasive procedures and minimum injury risk to subjects. Protection of human subjects is discussed in the following four sections:

F.2.1. Risk to the subjects

- *Human subject involvement and characteristics.* This study will collect anthropometric and cab workspace data for 900 firefighters across 4 regions of the U.S. The age range will be 18 and over.

There will not be any questions on health status. However, because this survey only includes current firefighters, all subjects are expected to be reasonably healthy for this project.

- *Privacy issues*. Three sources of data will be collected: demographic data with fire-apparatus-use questions, subject anthropometric and workspace measurements, and 3D scans. All sources of data will be used for research purposes. A photo (3D scan) consent form will be offered.
- *Physical risk.* The laser used in the whole body scanning is rated Class 1 by the Food and Drug Administration and, therefore, does not pose any known risk. A Class 1 laser, similar to the energy level of cashier scanners in grocery stores, is considered to be incapable of producing damaging radiation levels and is therefore determined to be eye safe.

F.2.2. Adequacy of protection against risks

- *Informed consent.* The survey will be conducted in a field lab near fire stations in and around the following major data collection sites: Baltimore MD, Chicago IL, Phoenix AZ, and Dallas TX. The time and locale of the study will be arranged with area fire stations through NFFF, IAFC, IAFF, and NFPA partnerships. Before subjects participate in this survey, they will be required to read and sign a consent form.
- *Privacy protection.* All subject data will be managed in accordance with the Privacy Act and the NIOSH HSRB informed consent procedures. All forms and computer data will be coded with a randomly assigned number to ensure privacy. Only the project officer will have access to the random number assignments. The data will be kept in locked cabinets in Room 1502. Only Richard Whisler (NIOSH data processing technician) and the project officer have access to the data and they will be responsible for the secure transfer of custody of the data to a different project officer in the event of a change in assignment.

F.2.3. Potential benefits of the proposed research to the subjects and others

Subjects, who are firefighters, and their firefighter colleagues will benefit from the proposed research because the study results will help improve automotive fire apparatus design so that firefighters could work in a more user-friendly environment which, in turn, will reduce risk of injuries.

F.2.4. Importance of the knowledge to be gained

U. S. firefighter anthropometric and workspace data are important in the design of ergonomically efficient fire-engine cabs, seats, restraint systems, egress, and bunker gear. Without these data, the apparatus may not provide a good fit to its end-users (i.e., firefighters), which in turn will result in injury risks to them.

F.3. Office of Management and Budget (OMB)

This project will not need OMB review.

F.4. Staff Health and Safety Plan

A staff health and safety plan is not needed for this project. No biological, chemical, radioactive, or other known hazardous substances will be used. The laser used in the whole body scanning is rated Class 1 by the Food and Drug Administration and, therefore, does not pose any known risk. Although the data collection will be conducted in the field, the staff will work in a temperature-controlled field lab, which is equivalent to an indoor laboratory in a fixed location. There are no identifiable risks.

G.) Vertebrate Animals: Not Applicable.

H.) Literature Cited

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