UNIVERSITY OF CALIFORNIA

Los Angeles

# Glovebox Gloves: Ergonomics Evaluation and Guidelines for the Prevention of Musculoskeletal Disorders

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Environmental Health Sciences

by

Peng-Cheng Sung

2006

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

UMI Number: 3240935

Copyright 2006 by
Sung, Peng-Cheng

All rights reserved.

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI®

UMI Microform 3240935
Copyright 2007 by ProQuest Information and Learning Company.
All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

© Copyright by

Peng-Cheng Sung

2006

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The dissertation of Peng-Cheng Sung is approved.

Shane S Que Hee

Shane S. Que Hee

Curtis D. Eckhert

Weng Kee

Weng Kee Wong

William C Hinds

William C. Hinds, Committee Chair

University of California, Los Angeles

2006

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# DEDICATION

With a deep sense of gratitude, I would like to thank my mother, Chu-Chu, my sister, Wan-Li, and my wife, Chiung-Wen, for their constant affection and encouragement. I would also like to thank my kids, Ivan and Grant, for their company during my study. To them I dedicate this dissertation.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# TABLE OF CONTENTS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**APPENDICES**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## LIST OF FIGURES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# LIST OF TABLES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# ACKNOWLEDGMENTS

I would like to thank my advisor Professor William C. Hinds for his guidance and inspiration through this research. Without his constant enthusiasm and encouragement, this dissertation could not have been accomplished.

I would like to acknowledge my committee members, Professor Shane Que Hee, Professor Curtis Eckhert, and Professor Weng Kee Wong, for their interest and support on this dissertation.

I am indebted to Dr. Victor Liu for the encouragement and support he has given me during my academic years. In addition, I would like to acknowledge the contribution of all of the participating subjects.

Finally, I would like to acknowledge the NIOSH Southern California Education and Research Center Training Pilot Project Grants for partially supporting this work.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# VITA

| | |
|---|---|
| April 15, 1967 | Born, SungWu, PingChen, TaoYuan, Taiwan |
| 1989 | B. A., Mechanical Engineering<br>National Cheng Kung University<br>Tainan, Taiwan |
| 1995 | M. S., Industrial Engineering<br>Rutgers University<br>New Brunswick, New Jersey |
| 1998 | M. S., Environmental Health Sciences<br>University of California<br>Los Angeles, California |

## PUBLICATIONS AND PRESENTATIONS

Boucher, T.O. and Sung, P.C. (1994). Developing a Class of Sequential Function Charts from Petri Nets. Proceeding of the International Conference on Computer Integrated Manufacturing and Automated Technology, IEEE Computer Society Press, 4th, pp. 163-168.

Liu, V.W.C., Sung, P.C., Arias, L., Hollander, J., and MacDonald, J. (2000). Use of glovebox gloves and its ergonomic impacts. AIHCE Abstract, pp. 10.

Liu, V.W.C., Sung, P.C., Hinds, W., and Froines, J. (2005). A remote control system for an eight-channel cascade impactor. AIHCE Abstract, pp. 178.

Sung, P.C. and Liu, V.W.C. (1999). Coefficient of dynamic friction of fingertip skin: effects of gender, texture and normal force. AIHCE Abstract, pp. 10.

Sung, P.C. and Liu, V.W.C. (2002). Effects of glovebox gloves and task positions on contact force. AIHCE Abstract, pp. 11.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# ABSTRACT OF THE DISSERTATION

Glovebox Gloves: Ergonomics Evaluation and Guidelines for the Prevention of Musculoskeletal Disorders

by

Peng-Cheng Sung
Doctor of Philosophy in Environmental Health Sciences
University of California, Los Angeles, 2006
Professor William C. Hinds, Chair

The goals of this study were to evaluate the glovebox gloves and recommend design/selection guidelines to offer the desired hand protection against ergonomic-related risk factors without compromising hand performance. Three commercially available glovebox gloves, namely butyl, hypalon, and neoprene in 0.015" and 0.03" thickness, were evaluated objectively and subjectively to establish guidelines to minimize the effects on hand performances. Task simulations for roller, tweezers, and wrench were performed to estimate the mechanical stress to establish guidelines to optimize protection. Glove properties were also measured and their strengths of association with objective hand performance and contact forces were tested. In addition,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the effects of gloving conditions on objective hand performance and mechanical stress were evaluated.

The results indicated that the gloved hands decrease grip strength and impair subjective hand performances. Gloved hands also increased mechanical stress compared to bare hand at the index finger for roller tasks, at the thumb and index finger for tweezers tasks, and at the middle finger for wrench tasks. In addition, gloved hands decrease mechanical stress compared to bare hand at the ring finger for roller tasks where.

Butyl and hypalon materials retain better grip strength than neoprene material. Butyl material performed best in subjective hand performances. Hypalon material decreased the mechanical stress compared to neoprene material and butyl material for roller and wrench tasks, respectively. In addition, neoprene material decreased mechanical stress compared to butyl material for tweezers tasks. Thin gloves retain better hand performances compared to thick gloves. Thin gloves also decreased mechanical stress compared to thick gloves for roller and wrench tasks. Single gloving retained better grip strength. Single gloving also recorded lowest mechanical stress at the ring finger for roller tasks. However, triple gloving recorded lowest mechanical stress at the thumb and the index and middle fingers for roller tasks. Triple gloving also recorded lowest mechanical stress for tweezers and wrench tasks.

The "Glovebox Design/Selection" software package has been created to facilitate the users to find the "best design" and "quick selection" guidelines for tool (s) to accomplish the desired hand protection without compromising the hand performances.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# Chapter 1

## Specific Aims and Hypothesis

This Chapter stated the specific aims and the null hypotheses associated with the specific aims to be tested in this study.

### 1.1 Specific Aims

The specific aims of this study are:

(1) Evaluate the objective effects of glovebox gloves (butyl, hypalon, and neoprene), gloving conditions (barehanded, single, double, and triple gloving) and their intrinsic properties (thickness, coefficient of static friction) on hand performances in terms of maximum grip and key pinch strength, and mechanical stress on palmer skin;

(2) Evaluate the subjective effects of glovebox gloves on hand performances in terms of tactility, tingling sensation, and comfort.

(3) Estimate the tendons and muscles forces of thumb and fingers using biomechanical model; and

(4) Formulate ergonomics guidelines for glovebox gloves design/selection through gloves evaluation and laboratory tasks simulation.

### 1.2 Null Hypothesis

The null hypotheses for maximum grip strength with $\alpha = 0.05$ of the present study are:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(1) $H_0$: There is no difference in maximum grip strength between bare and gloved hands.

(2) $H_0$: There is no difference in maximum grip strength between three glove materials.

(3) $H_0$: There is no difference in maximum grip strength between two glove thicknesses.

(4) $H_0$: There is no difference in maximum grip strength between three gloving conditions.

The null hypotheses for maximum key pinch strength with $\alpha = 0.05$ of the present study are:

(1) $H_0$: There is no difference in maximum key pinch strength between bare and gloved hands.

(2) $H_0$: There is no difference in maximum key pinch strength between three glove materials.

(3) $H_0$: There is no difference in maximum key pinch strength between two glove thicknesses.

(4) $H_0$: There is no difference in maximum key pinch strength between three gloving conditions.

The null hypotheses for subjective hand performance with $\alpha = 0.05$ of the present study are:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(1) $H_0$: There is no difference in subjective hand performances between bare and gloved hands.

(2) $H_0$: There is no difference in subjective hand performances between three glove materials.

(3) $H_0$: There is no difference in subjective hand performances between two glove thicknesses.

The null hypotheses for palmar contact forces with $\alpha = 0.05$ of the present study are:

(1) $H_0$: There is no difference in palmar contact forces between bare and gloved hands.

(2) $H_0$: There is no difference in palmar contact forces between three glove materials.

(3) $H_0$: There is no difference in palmar contact forces between two glove thicknesses.

(4) $H_0$: There is no difference in palmar contact forces between three gloving conditions.

The null hypotheses for tendon and muscle forces with $\alpha = 0.05$ of the present study are:

(1) $H_0$: There is no difference in tendon and muscle forces between bare and gloved hands.

(2) $H_0$: There is no difference in tendon and muscle forces between three glove

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

materials.

(3) $H_0$: There is no difference in tendon and muscle forces between two glove thicknesses.

(4) $H_0$: There is no difference in tendon and muscle forces between three gloving conditions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# Chapter 2

## Background and Significance

This chapter provides a review of the literature in the following areas: (1) glovebox gloves usage, (2) glove effects on objective hand performance, (3) glove effects on mechanical stress, (4) glove effects on subjective hand performance, (5) glove properties, and (6) glove size effect, and (7) existing guidelines and essential elements of ergonomics-based guidelines.

### 2.1 Glovebox Gloves Usage

Gloveboxes have been frequently used in industry (biologicals, microelectronics, nuclear, and pharmaceutical), governmental laboratories and various research institutes to protect workers from hazardous chemicals or microorganisms, and nuclear materials or to protect products from environmental contamination (Eastman Kodak Company, 1983). In glovebox operations, workers are required to wear gloves to offer protection to the hand against hazardous chemicals, biological, mechanical and radiological hazards. However, wearing gloves is known to impair hand performances such as dexterity (Nelson and Mital, 1995), range of motions (Bellingar and Slocum 1993), strength (Kovacs et al. 2002), and tactile perception (Novak et al. 1998). Reduced hand performances may lead to forceful exertions and awkward hand/wrist postures that have been recognized as risk factors associated with the development of musculoskeletal disorders (MSDs) in the hand and wrist (NIOSH, 1997). Therefore, ergonomics guidelines for manufacturing and usage of glovebox gloves should be developed and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

established to accomplish the desired hand protection against ergonomic-related disorders.

To establish the ergonomics guidelines to provide effective prevention for MSDs in the hand and wrist, this study evaluated commercially available glovebox gloves according to two sets of variables. The first set of variables is based on the effects of glovebox gloves and their intrinsic properties on hand performance and mechanical stress that are quantitatively measured. The second set of variables is based on the user's subjective evaluation of the gloves on hand performances. The objective variables included in the first set are hand performances parameters (maximum grip and key pinch strength) and mechanical stress (contact forces on palmer skin and the tendons and muscles forces). The subjective variables selected for the second set are tactility, tingling sensation, and comfort.

### 2.1.1 Double & Triple Gloves

In glovebox applications, workers may require wearing up to three layers of gloves while performing tasks. Wearing double gloves had significant benefit in protection the hands from exposure to contamination and blood-borne infections (Pieper et al. 1995; Marin-Bertolin et al. 1997; Kovavisarach and Vanitchanon 1999; Naver and Gottrup, 2000) and can also enhance pressure tolerance of the hands (Muralidhar and Bishu 2000). However, hand performances in terms of sensibility (tactility) (Watts et al. 1994; Wilson et al. 1996), dexterity (Plummer et al. 1985; Wilson et al. 1996) and grip strength (Muralidhar et al. 1999) are impaired on double gloving. No articles were

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

found discussing the effects of gloving conditions on mechanical stress and the effects of triple gloving on grip and pinch strength. These effects of gloving setting have yet to be explored.

## 2.2 Glove Effect on Objective Hand Performance

Two objective hand performances, namely grip and key pinch strength, are included for evaluation in this study. Grip strength is the muscular power and force of the hand when an object is held in a clamp formed by the partially flexed fingers on one side and the thumb on the other (Napier 1956). Published literature has indicated that the effect of gloves on grip strength capabilities are consistent in the sense that gloves decrease strength compared to the bare hand condition (Cochran et al. 1986; Bishu et al. 1987; Sudhakar et al. 1988; Wang 1991; Hallbeck and McMullin's 1993; Batra et al. 1994; Muralidhar and Bishu 1994; Bishu and Klute 1995; Tsaousidis and Freivalds 1998; Muralidhar et al. 1999; Buhman et al. 2000; Rock et al. 2001; Kovacs et al. 2002). The reduction compared to bare hand ranged from 3.7% of synthetic rubber to 50.0% of extra vehicle glove. The possible reasons for the reduction are reduction in inter-digit distances and reduction in range in motion (Buhman, et al. 2000), earlier pressing of the fingers with each other (Bishu and Klute 1995), interference of the glove in closing the hand around objects and the interference of the glove in tactile feedback (Cochran et al. 1986 and Batra et al. 1994), reduction in inter-digital pressure (Batra et al. 1994), and interference with digital flexion (Hallbeck and McMullin 1993).

Pinch strength is the force generated by the opposing thumb tip to index fingertip

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(tip pinch), thumb pad to lateral aspect of the middle phalanx of index finger (key pinch), or thumb pad to pads of index and middle fingers (palm pinch) (Mathiowetz et al. 1985). Lack of effects of gloves on pinch strength has been reported. Bishu and Klute (1995) showed that the reduction in maximum pulp pinch strength of the gloved hand is very small (around 10%) compared to the bare hand. Rock et al. (2001) also showed that there was a statistically significant difference between bare hand and leather glove on three-point pinch strength. However, Tsaousidis and Freivalds (1998) indicated that there was no statistically significant effect of gloves on maximum tip pinch strength. In addition, Muralidhar and Bishu (1994) found that maximum pinch strength increased slightly for the gloved hands over the bare hand.

### 2.3 Glove Effect on Mechanical Stress

Mechanical stresses included in this study are contact forces on palmar skin and tendon and muscle forces.

#### 2.3.1 Contact Forces on Palmar Skin

Glovebox gloves usage may result in aggravated pressure (contact forces) in the hand and wrist regions when performing glovebox tasks. In addition, working through glovebox glove ports may restrict ranges of motion of the shoulder and elbow. This limits the utilization of the most powerful muscle groups during lifting and force-exerting tasks and putting more stress on the hands and wrists (Eastman Kodak Company 1983). High external surface pressure is the cause of work-related

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

deformations of the hand such as blisters, callosities and occupational stigmata (Fraser 1980). In addition, excessive stress imposed on the fingers may result in painful compression of arteries, veins and nerves. High compression on the hand will also cause tissue irritation, followed by inflammation and formation of callus tissue (Tichauer and Gage 1977).

### 2.3.2 Tendon and Muscle Force

Repeated and sustained forceful exertions with insufficient recovery time may increase the stress on muscles and tendons which are associated with the development of musculoskeletal disorders (Hallbeck et al. 1995). Assessment of tendons and muscles forces can better the understanding of hand function and can be used to evaluate mechanical causes for hand pathologies associated with the using of hand tools. In addition, it can help the physician in planning the best recovery of the mechanical function of an injured hand.

## 2.4 Glove Effect on Subjective Hand Performance

This section reviews the glove effect on the following subjective performances: tactility, comfort, and tingling.

### 2.4.1 Tactility

Tactility is defined as sensitivity to temperature, texture, weight, size, and shape, as well as other attributes that can be sensed through touch (Buhman et al. 2000). Use of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

gloves had been reported to reduce tactility and affect the amount of force exerted to hold or manipulate a given object (Putz-Anderson, 1988). In contrast, no significant effect of extra vehicle activity (EVA) gloves on tactility has also been reported by Bishu and Klute (1995). For latex examination gloves, mixed effects have been reported. Neiburger (1992), Watts et al. (1994), and Novak et al. (1998) found a significant influence of gloves on tactile discrimination while no significant influence of latex gloves ranging in thickness from 0.21 mm to 0.83 mm in thickness were reported by Nelson and Mital (1995). In addition, Thompson and Lambert (1995) found significant effects of latex gloves on two of their four tactile sensitivity tests. Since different methods were used in these studies, the lack of agreement between studies of gloves may due to the types of measurements taken.

### 2.4.2 Discomfort

Discomfort is mental or bodily distress (The Free Dictionary). Discomfort has been cited indirectly as a potential contributor to cumulative trauma disorders (Armstrong, 1986; Putz-Anderson, 1988). Muralidhar and Bishu (2000) showed that the pressure-discomfort levels for cotton jersey gloves are significant higher than for the bare hand indicating that wearing cotton jersey gloves will increase comfort compared to bare hand when encountering mechanical trauma caused by sustained pressure on the hand. Roberts and Brackley (1996) used a five-point scale (1: worst, 5: best) for comfort score measurement. The results illustrated the preference for hydrogel-coated gloves over normally used latex gloves for short and long-term wear comfort. Wilson et al.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(1996) compared the subjective effects of single and double gloves on comfort where thirty-two surgeons were asked to give a score on comfort as follows: excellent (5), very good (4), good (3), fair (2), and poor (1). The results showed that double gloves significantly reduced the comfort when compared with single glove. The level of comfort between glovebox gloves and bare hand were assessed in this study.

### 2.4.3 Tingling

Tingling occurs because of abnormal nerve sensations (Shand's health care). It is an indication of damage or irritation to the nerves. One of the possible causes is due to continued and repeated pressure leading to numbness and nerve damage. Tingling has also been used as one of the subjective diagnostic criteria for Carpal Tunnel Syndrome (Gross, 1988; Rossier and Blair, 1984). No studies were found assessing the effects of gloves on tingling in the fingers.

## 2.5 Properties of Glove Materials and their Potential Effects on Hand Performance & Mechanical Stress

The glove properties that change hand performance and mechanical stress magnitudes should be understood and can also serve as selection guidelines for currently available and potential glove materials. Published literature has shown that material thickness increased the effective handle size that reduces the maximum force capability (Riley 1985; Bishu et al. 1987; Kinoshita 1999). Batra et al (1994) and Wang (1991) also showed that the extent of reduction in grip strength was correlated significantly with

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

glove thickness. Low static coefficient of friction of glove surface increased grasp force required (Groth and Lyman 1958; Bishu et al. 1987; Kinoshita et al. 1995; Bronkema-Orr et al. 1996). Batra et al (1994) also indicated that the grip strength and coefficient of static friction are significantly correlated. Tsaousidis and Freivalds (1998) stated that higher glove pliability decreased tactile information and increased force exertions. However, the effects of glove pliability on hand performance and mechanical stress have not been evaluated. This study measured the coefficient of static friction and pliability of glove materials and conducted a correlation analysis to evaluate the significance of these glove characteristics (glove thickness, coefficient of friction, and pliability) on grip and key pinch strength and mechanical stress (contact forces).

### 2.6 Glove Size on Hand Performance

Chen et al. (1989) found that glove size was not a factor for torque exertion and for performance time. Moore et al. (1995) indicated that tighter fitting latex gloves performed better in terms of dexterity compared to regular fit gloves. Thompson and Lambert (1995) showed no significant differences between best-fitting and ill-fitting latex gloves for four tactility tests. Kovacs et al. (2002) found that maximum grip strength in oversized latex with power lining glove was significant lower than the best fit latex with powder lining gloves. However, no differences in strength between best fit and oversized leather and jersey cottons gloves were found. Hamann et al. (1993) stated that wearing oversized gloves impaired dexterity and grip strength while wearing undersized gloves can cause hand fatigue. The available evidences can only verify that

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

oversized gloves impair grip strength. The research objective of this study did not include the effects of glove size. Two hand sizes, 8.5"and 9.75" of glovebox gloves were provided and the subject wore both of the gloves to pick the best fit glove.

## 2.7 Existing Guidelines and Essential Elements of Ergonomics-Based Guidelines

The testing protocols for glove design guidelines to optimize protection against chemical (e.g. permeation resistance: ASTM F739), physical (e.g. puncture resistance: ASTM F1342) and biological (e.g. pathogenic resistance: NFPA 1999, Sections 6-9 and 6-10) have been established. However, there are currently no established ergonomics guidelines for glove designs except ASTM F2010 for the dexterity test.

The ergonomics guidelines to be implemented for glovebox gloves should optimize protection without compromising hand performance. The guidelines should address the following issues:

1. Minimize effects of glovebox gloves on natural hand performance

   To minimize effects on hand performances, it is imperative that forceful exertions and tingling sensations be minimized and good tactile perception and comfort be maintained. The guidelines to be established should specify the types of glove materials and the range of glove properties to be followed through evaluation of currently available gloves and potential glove materials if possible (this study evaluated current commercially available gloves only) to minimize glovebox glove effects on hand performances.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2. Optimize protection

To optimize protection, the hand and glove/tools contact areas that are subject to high mechanical stress (critical areas) should be identified and the stress on critical areas should be minimized. In addition, the additional strain posed by the use of gloves on both the tendons and muscles of the hand should be identified and minimized. The mechanical stress in the identified critical areas for intended tasks could also be minimized by increasing the thickness of gloves with selected materials around critical areas without increasing the thickness of the whole glove. This will provide adequate protection without decreasing the tactility sensitivity of the unaffected areas and the degradation of hand performance could be minimized (Muralidhar et al. 1999; Muralidhar and Bishu 2000).

Work-related musculoskeletal disorder is a public health issue. Glove usage could result in risk factor (ex. forceful exertions and high contact stress) associated with the development of musculoskeletal disorders in the hand and wrist. Those risk factors should be identified and reduced to improve the safety and health in the work environment. Currently, the concentration of public health in glove is to prevent perforations, blood-borne infections, and contaminants. Glove should also be selected and designed to prevent the risk factors associated with the development of musculoskeletal disorders in the hand and wrist. For general public, the test protocols established for glovebox gloves could be adopted to evaluate the glove to reduce the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

potential risk factors. In addition, the material, thickness, or layer conditions can be adopted for general public if similar situations occur.

The ergonomics guidelines based on minimizing glovebox glove effects on hand performance will prevent the risk factors of forceful exertions associated with the development of MSDs in the hand and wrist. In addition, the critical areas can be identified to minimize the stress on those hand/wrist regions and reduce the chance of accidental breach, wear, and tear of gloves to offer the desired protection for the hand against hazardous chemicals, biological, mechanical and radiological hazards.

This study represents an integration of ergonomics principles and sensor technology for evaluating glovebox gloves and establishing ergonomics guidelines for gloves design and usage. This study also has direct application in improving glove manufacturing design and the associated test protocols for industrial personal protective gloves to provide appropriate prevention for work-related musculoskeletal disorders in the hand and wrist. In addition, the data collected in this study have potential value for tool and task improvement.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# Chapter 3

# Methodology

The methodology section is divided into four parts. Each part addresses a specific aim of this study.

## 3.1 Evaluate the Objective Effects of Glovebox Gloves, Gloving Condition, and Their Intrinsic Properties on Hand Performance and Mechanical Stress

Hand performance will be investigated in terms of maximum grip and key pinch strength. Mechanical stress between the hand and glove/tool interface will be measured through tasks simulation of three hand tools using force sensing resistors (FSRs).

### 3.1.1 Subjects

Eleven unpaid volunteered subjects free of musculoskeletal disorders/injuries (MSDs) in the upper extremities of UCLA female students or wives of UCLA male students comprised the subject pool. The subject free of MSDs status in the upper extremities was identified through interviewing during the recruiting process. All eleven subjects participated and completed the maximum grip strength and maximum key pinch strength measurements and the simulation tweezers tasks while ten subjects completed the simulated roller and wrench tasks. All these subjects are right handed. The mean values of age, height, hand length and maximum breadth of hand are 32 ± 5 years (23 to 40 years), 159.7 ± 5.0 cm (152.0 to 169.0 cm), 167.0 ± 5.1 mm (156.5 to 174.6 mm), and 87.2 ± 3.8 mm (79.4 to 93.4 mm), respectively. The total time for a subject to complete

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

all the tests ranged from 40 ~ 50 hours. Each subject performed the tests twice/week and each session lasted 2 to 2.5 hours. In average, 16 to 18 sessions (2 to 2.5 months) were required for each subject to complete all the tests.

The UCLA Institutional Review Board (UCLA IRB) approved this study and a copy of the approval notice is attached (Appendix 1). The subjects were recruited through a flyer given to them from friends of the principal investigator. Then, the principal investigator contacted the prospective subjects personally to state the purpose of the study, the procedures, and the potential risks. Each volunteered subject signed an informed consent statement (Appendix 2) that was approved by UCLA IRB at the very beginning of the experiments. Minor hand and finger discomfort may be experienced while participating in this study. The subjects were informed that they may choose at any time to discontinue the test should the discomfort occur.

### 3.1.2 Apparatus

This section describes the apparatus used in the present study.

#### 3.1.2.1 Glovebox

A typical glovebox (Figure 1) used in glovebox applications was adopted in this study. The height and width of the glovebox are 3.77 (72") and 0.82 (32") meters. The floor dimensions inside the glovebox are 0.8 m (31.5") * 0.8 m (31.5"). The diameter of the glove port is 20.3 cm (8"). The distance between the centers of the two glove ports is 45.7 cm (18"). A wood stand of height 16.0 cm was also provided to adjust the height for performing the tasks if required.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

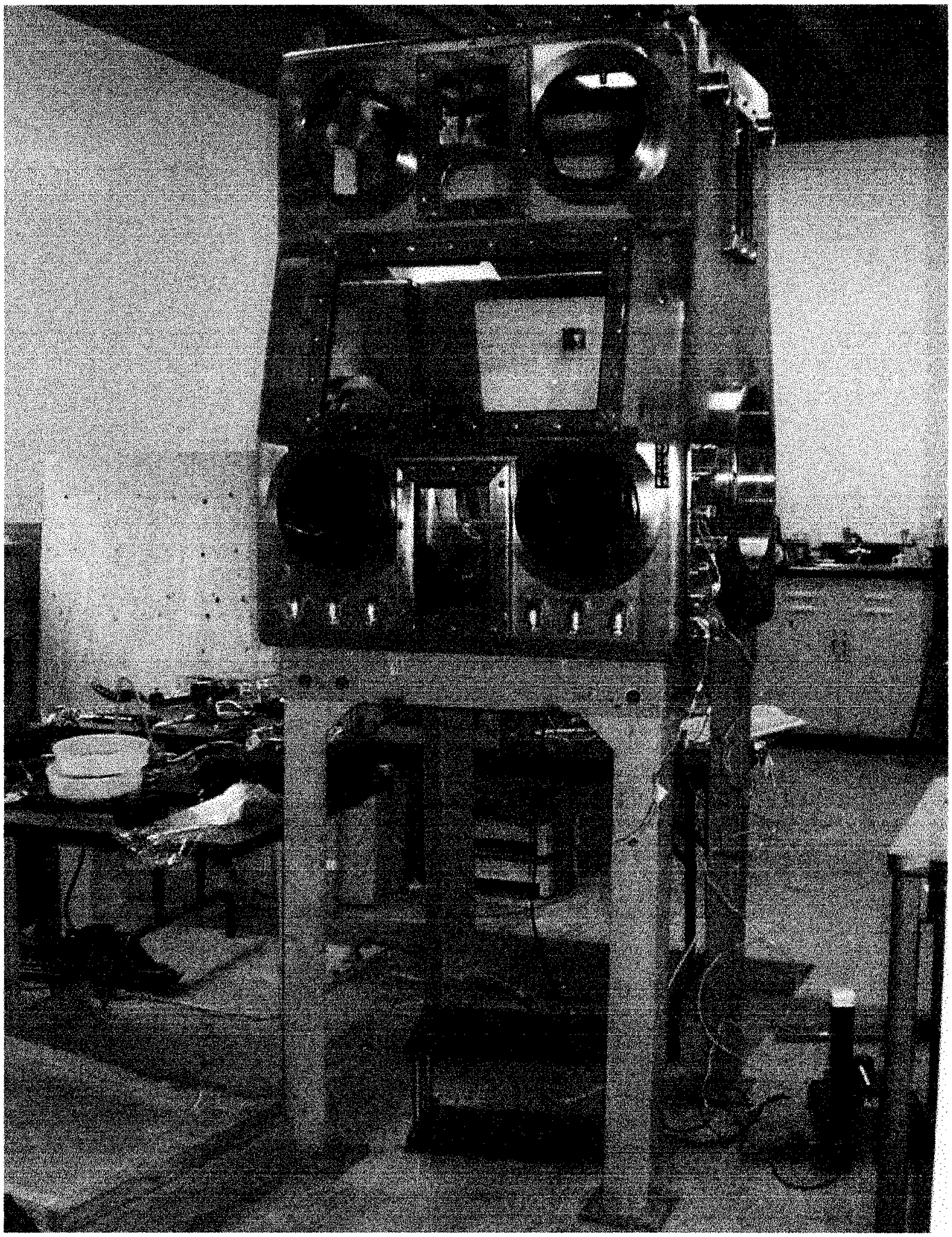


Figure 1 Glovebox

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

#### 3.1.2.2 Gloves

Butyl, hypalon and neoprene gloves (Figure 2) in two different thicknesses (0.015" and 0.03") that are commercially available for glovebox use were selected for evaluation. The cuff diameter and length of the gloves are 8" and 32". Two hand sizes, 8.5"and 9.75" were provided and the subject wore both of the gloves to pick the best fit glove. These gloves are the two smallest sizes of the available glovebox gloves.

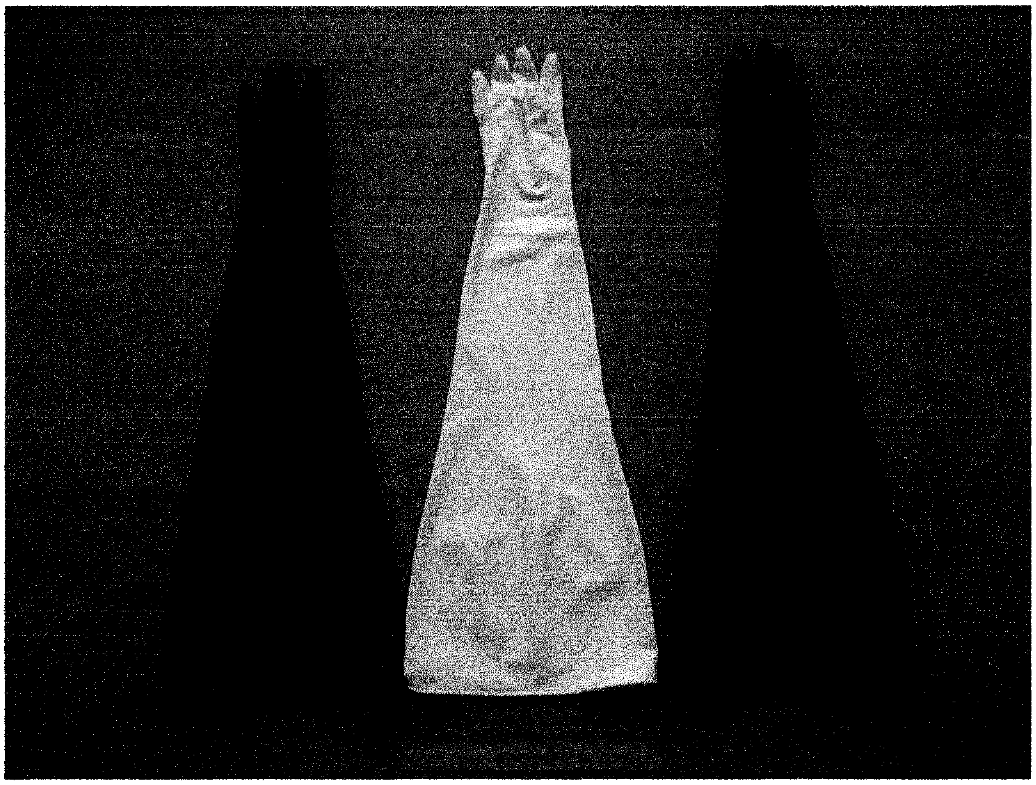


**Figure 2 Butyl, hypalon, and neoprene glovebox gloves from left to right with a one foot ruler**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

For the single gloving condition, the subject donned only a pair of glovebox gloves. The double gloving condition includes a pair of glovebox glove as outer glove and a pair of natural rubber (Trionic© size 8, 0.02" thickness, 43.5 gm) gloves as the inner glove which was used in glovebox work to facilitate donning the outer glove. The triple gloving condition adds another pair of cotton gloves (median size, 0.008" thickness, 9.3 gm) as the innermost glove which is used in glovebox work for perspiration absorption purpose. Figure 3 shows the natural rubber and cotton gloves.

**Figure 3 Cotton (left) and natural rubber (right) gloves with a one foot ruler**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 3.1.2.3 Hand Tools

Three hand tools (Figure 4), namely a roller, a crescent wrench (3/4"), and a pair of tweezers were used for task simulations in this study. These tools are used for glovebox work and for common maintenance/production activities in the nuclear industry. These tools were chosen based on reviewing the videotape of the glovebox operations handling radioactive materials (Liu et al. 2000). The weight, length, and maximum handle width of these tools are listed in Table 1.

**Table 1 Dimension and weight of the hand tools**

| | Weight (g) | Length (cm) | Handle Width (cm) |
|---|---|---|---|
| **Roller** | 440.00 | 10.40 | 2.55 |
| **Tweezers** | 65.30 | 23.30 | 1.18 |
| **Wrench** | 187.50 | 16.33 | 1.58 |

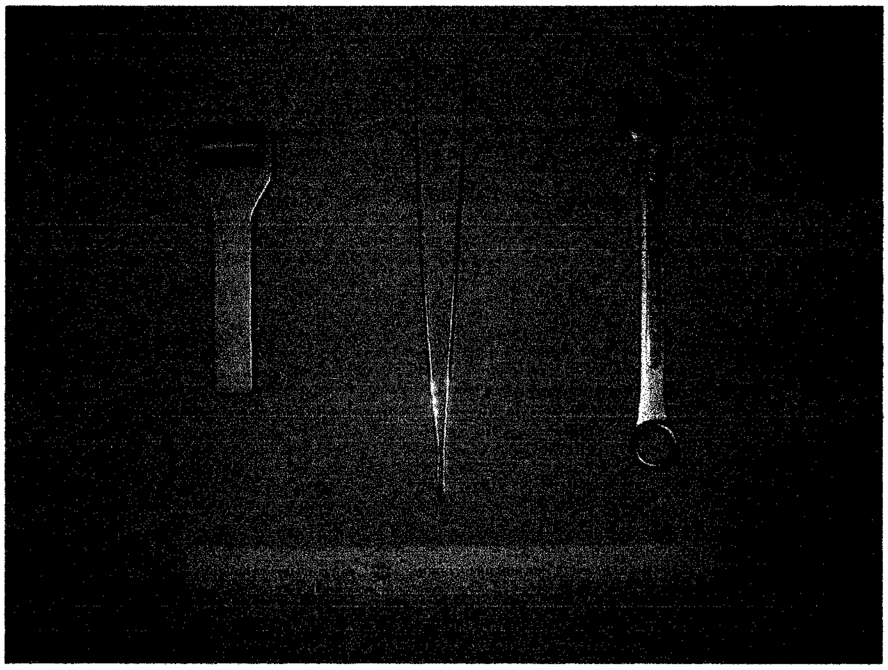


**Figure 4 Three hand tools: roller (left), tweezers (middle), and wrench (right)**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 3.1.2.4 Force Sensing Resistors

Thin-film force sensing resistors (FSRs, Figure 5), with capacity of 0 to 111.2 N (25 Lbf) and 9.5 mm diameter circular effective sensing area, by Tekscan Inc. were used in the determination of contact forces at hand and glove/tool interfaces. An aluminum dome with 1.5 mm height in the center and a width equal to the effective sensing area was glued on the sensing area to increase sensitivity and to direct the contact force through the effective sensing area (Jensen et al. 1991). A strain gauge dynamometer (Figure 6) constructed using a 177.9 N (40 lbf) strain gauge (OMEGA, LCL040) was used for calibrating the FSRs right before performing the simulated tasks. Nonlinear regression was used to calibrate the FSRs with the following double exponential equation based on previous study (Liu et al. 2000):

$$\text{Forces} = A_1 * \exp(B_1 * \text{Voltage}) + A_2 * \exp(B_2 * \text{Voltage}) \qquad (1)$$

where the $A_1$, $A_2$, $B_1$, $B_2$ are the parameters.

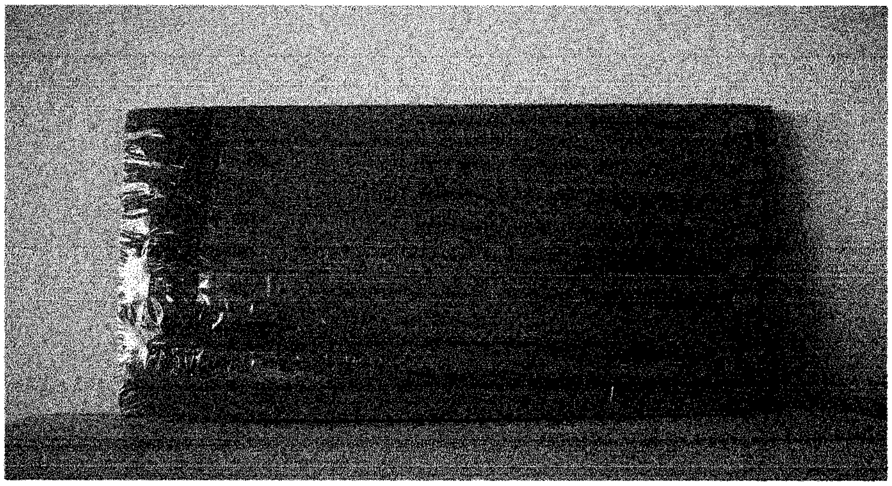


**Figure 5 Thin-film force sensing resistors**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

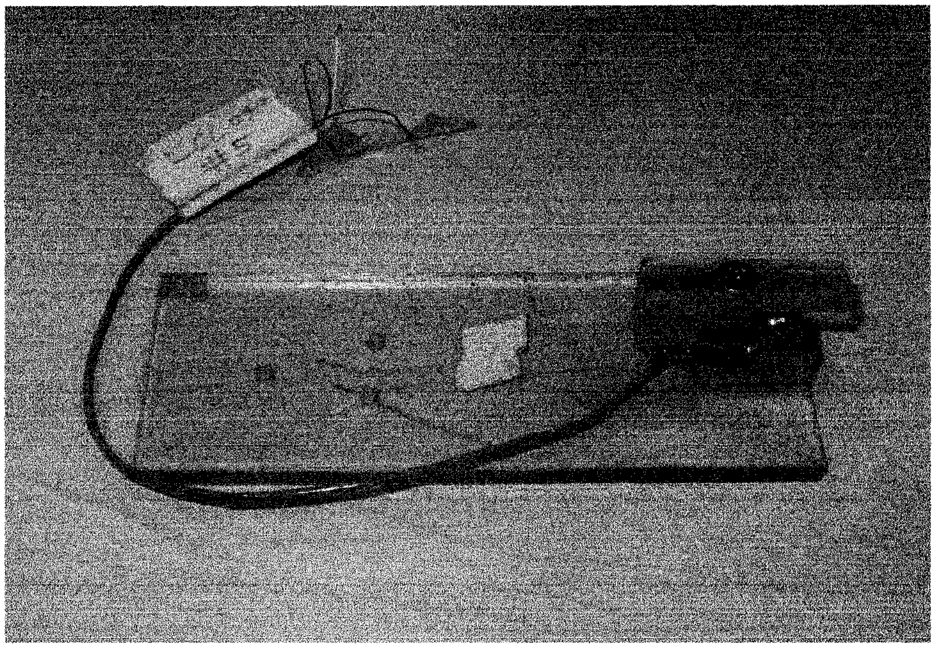


**Figure 6 Strain gauge dynamometer for FSRs calibration**

### 3.1.2.5 Force and Torque Sensors

A strain gauge dynamometer (Figure 7) constructed using a 22.3 N (5 lbf) strain gauge (OMEGA, LCL005) with 1.8 cm space between the two contact points was used for measuring the target force demand when performing the tweezers task simulations. Four OMEGA LCL040 strain gauges were used to support a polycarbonate plate (Figure 8) to measure the target force demand for roller task simulations. An OMEGA T5162 torque sensor (Figure 9) with torque capacity of 113 Newton-meter was used to measure the target torque demands for wrench task simulations. Linear regression was used to obtain the calibration of the strain gauges and torque sensor.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

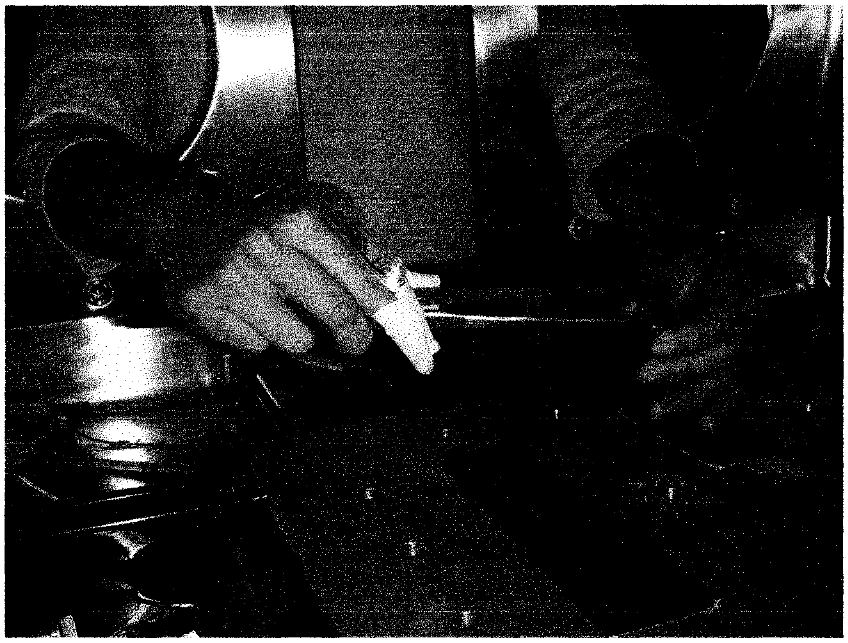


**Figure 7 A strain gauge dynamometer (holding in the left hand) for measuring target force demand for tweezers task simulations**

**Figure 8 Polycarbonate plate supported by four strain gauges to measure target force demands for roller task simulations**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

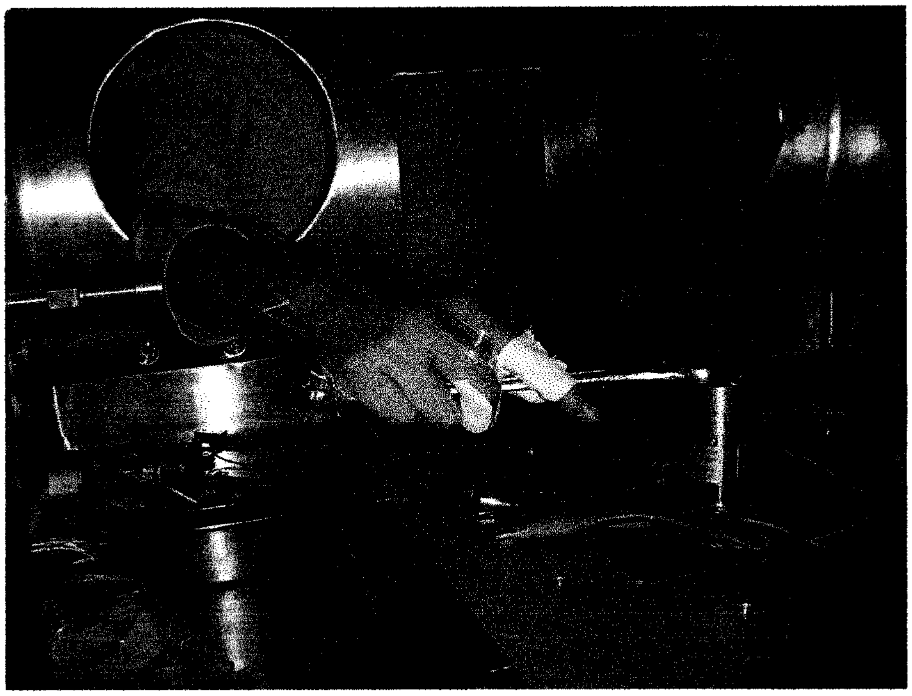


**Figure 9 An OMEGA T5162 torque sensor used to measure the target torque demand for wrench task simulations**

### 3.1.2.6 Power Supply, Amplifiers, A/D Converter Board

An Omega model PSS-5A (or PST-4130) power supply was used to provide 5 Vdc power to a breadboard where the FSRs were parallel connected. The same power supply was also used to provide 5 Vdc power to the strain gauges or the torque sensor. Up to four amplifiers (Omega model OCT-01) amplified the analog signal from the strain gauges or torque sensors with a gain of 100. An 8-channel data acquisition board (DAS 1601) and a 486-DX computer were then used to collect, process, and display the force or torque measurements. Figure 10 shows an electrical connection diagram outlining the experimental setup for data collection.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

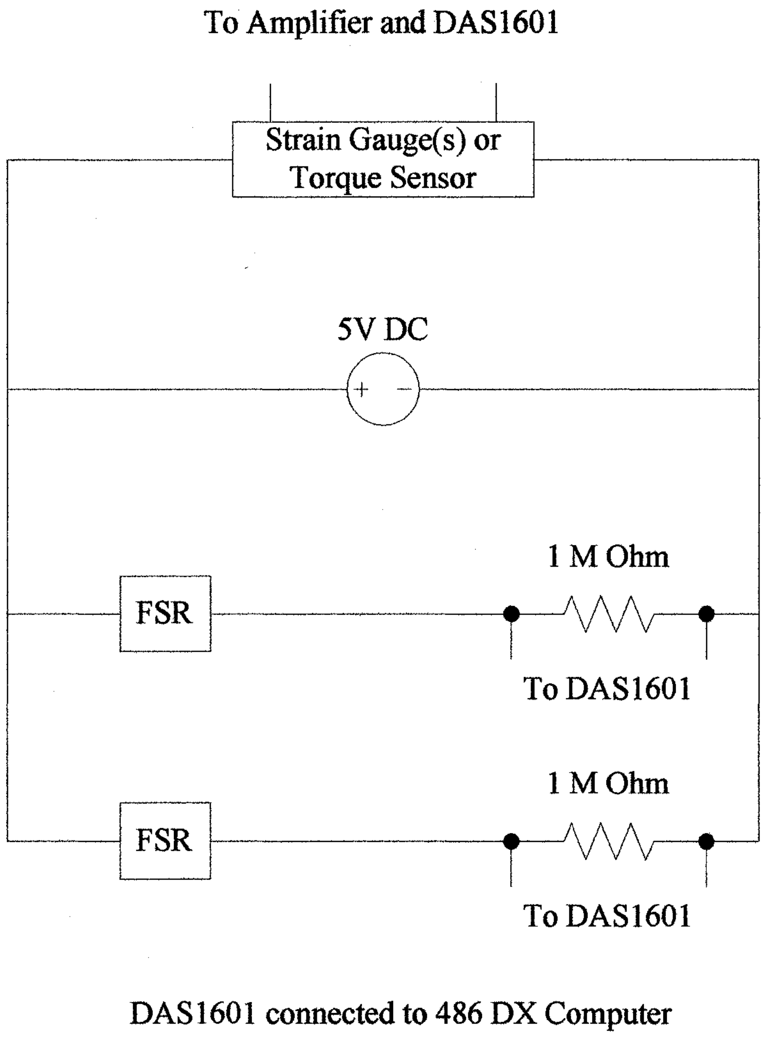


**Figure 10 Electrical connection diagram outlining the experimental setup for data collection**

### 3.1.3 Simulated Tasks

Simulated tasks were conducted inside a typical glovebox to determine the contact forces at the hand and glove/tool contact interfaces. During each 10 second sampling period, the subjects were asked to make exertion to reach the target task demand, then, hold that force or torque for approximately one second. The same

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

procedure was repeated three times. For roller and tweezers, the target task demands represented 25%, 50%, and 75% of the maximum voluntary force exertions of the tools measured from three female subjects in previous study (Liu et al. 2000). For wrench tasks, the highest target task demand represented 75% of the maximum voluntary torque exertions of three female subjects. The lowest and medium target task demands represented 1/8 and 1/2 of the highest target task demand due to wider range of the maximum voluntary torque exertions measured. The subjects were also asked to control the exertion force/torque to ±10% of the target task demand to minimize the variation of target task demand and to ensure the fulfillment of the specific task. The target task demand, i.e., a specific force/torque requirement was displayed on the screen of a computer monitor during the test. Application programs written in-house with TestPoint software package (ADAC Corp.) were used to show the exerting forces or torques. Then, the subjects were able to adjust the exerting forces or torques to within ±10% of the target task demand. The descriptions for each of the simulated task are as follows:

1) Roller: the subject will
    a) Roll the roller back and force on top of polycarbonate plate supported by four strain gauges located on the center of glovebox floor with 10, 20, 30 N target forces.
2) Picking with tweezers: the subject will
    a) Use a pair of tweezers to exert 5, 10, and 15 N force on a strain gauge dynamometer constructed at the laboratory using a 5 lbf (22.24 Newton) strain gauge (OMEGA, LCL005).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3) Wrenching: the subject will

   a) Use a crescent wrench to turn the ½" nuts fixed on top of the torque sensor (OMEGA T5162 with torque capacity of 113 Newton-meter) located on the center of the glovebox floor with 1.13, 4.52 and 9.04 Newton-meter (N-m) target torque strength.

### 3.1.4 Procedure

The experiment was conducted in three stages. In the first stage, the basic anthropometric measurements including height, weight, and hand dimensions were performed. The second stage involved the maximum grip key pinch strength measurements. In the third stage, the magnitude of mechanical stress between hand and glove/tools interface across the palmar hand surface were determined through laboratory tasks simulation conducted inside a glovebox.

#### 3.1.4.1 Anthropometry Measurements

The basic anthropometric measurements including height, weight, and hand dimensions were performed using tape measure, scale, and digital caliper for each subject. Eighteen hand dimensions, namely fingertip to root of digit 3 and 5, 1st joint to root of digit 3 and 5, 2nd joint to root of digit 3 and 5, depth at tip of digit 3 and 5, breadth at first joint of digit 3 and 5, breadth at second joint of digit 3 and 5, finger tip to knuckle of thumb, breadth at knuckles, maximum breadth of hand, length of hand, depth at knuckles, and circumference of hand were measured for each subject following

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

instructions described by Okunribido (2000). In addition, fingertip to root of digit 2 and 4 not described by Okunribido was also measured.

### 3.1.4.2 Grip and Key Pinch Strength

Maximum grip and key pinch strength for gloved and bare hand conditions were measured for each subject using a Jamar dynamometer and Jamar pinch gauge (Figures 11, 12 Lafayette instrument company). Caldwell's regimen (1974) was followed with a steady exertion sustained for four seconds and at least two-minute rest periods between exertions for the estimations of the maximum grip and key pinch strength. The subjects were seated with their shoulder adducted and neutrally rotated, elbow flexed at $90^0$, forearm in neutral position, and wrist between $0^0$ and $30^0$ extended and between $0^0$ and $15^0$ ulnar deviations to maintain neutral posture (Mathiowetz et al 1985). The investigator held the Jamar dynamometer or Jamar pinch gauge and asked the subject to build up his/her maximum voluntary contraction (MVC) for force exertions. Three replicates of maximum grip and key pinch strength within 10% tolerance of the mean score were recorded. A five minute break was given to each subject after twenty-five minutes test.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

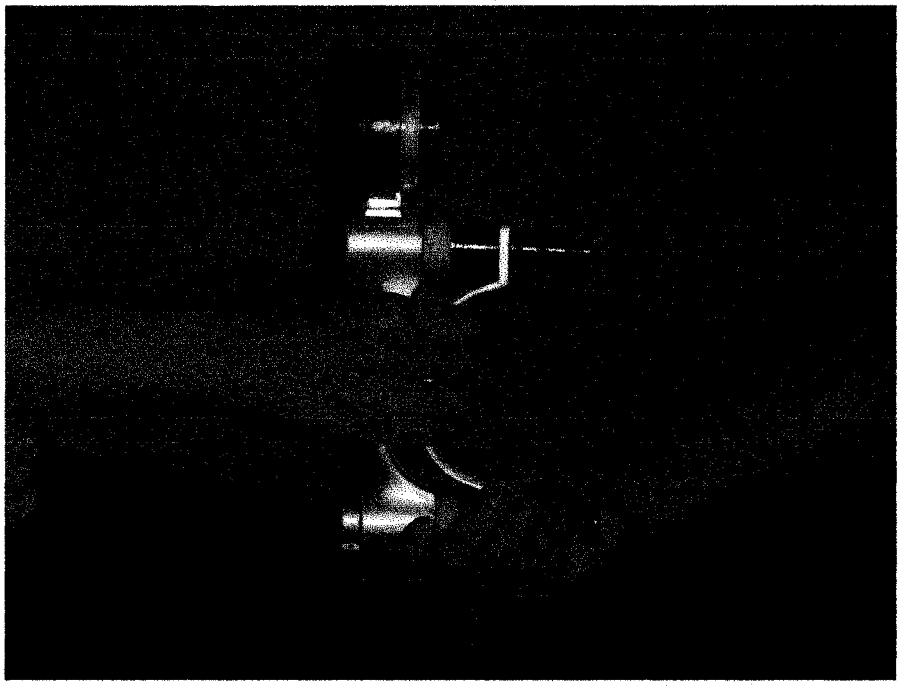


Figure 11 Maximum grip strength measurements using a Jamar dynamometer

Figure 12 Maximum key pinch strength measurements using a Jamar pinch gauge

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 3.1.4.3 Contact Force

The contact forces between hand and glove/tools interface across the palmar hand surface were determined through laboratory tasks simulations conducted inside a glovebox under neutral atmosphere (same atmosphere inside and outside). A maximum of four FSRs were attached using sports tape onto identified contact areas on the hand directly depending on the tasks. For roller tasks, the four FSRs were attached onto the tip of thumb, second phalange of index finger, tip of middle and ring fingers to measure the contact forces. For tweezers tasks, the two FSRs were attached onto the tip of thumb and tip of index finger to measure the contact forces. For wrench tasks, the four FSRs were attached onto the tip of thumb, second phalange of index finger, second phalange of middle finger, and palm region (H9) as shown in Figure 13 (adopted from Fransson-Hall and Kilbom 1993). These areas were decided based on contact areas previously identified (Liu et al. 2000 and Sung and Liu 2002) and past experience.

The contact forces (in Newton) measured in this study were also transformed into pressure (in kPa, Pa: 1 Newton per square meter) for comparison purposes using the following equation.

$$\text{Pressure (kPa)} = \text{Contact Forces (N)} / \text{Contact area of FSRs } (m^2) / 1000, \quad (2)$$

$$\text{Contact area of FSR} = pi * (\text{diameter of FSR} / 2)^2, \quad (3)$$

where diameter of FSR is equal to 0.0095 meter (0.95 cm) and pi is equal to 3.1415926.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

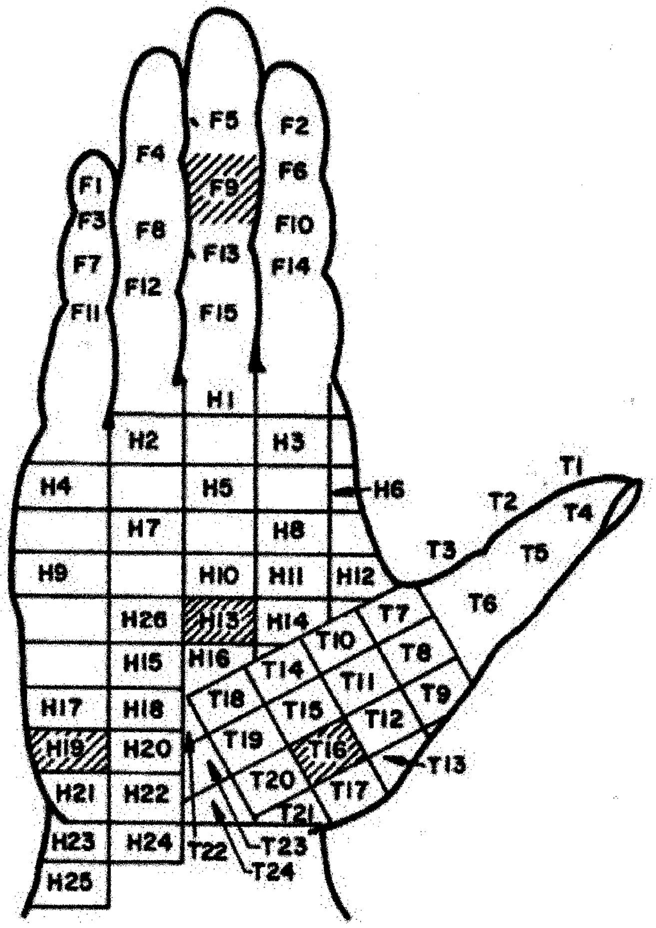


**Figure 13 Hand regions**

An analog/digital converter board (DAS 1601, Keithley Inc.) controlled by application programs written in-house with a TestPoint software package version 2 (Keithley Inc.) was used to collect, process, and display the contact forces magnitudes. Two or four channels of the converter board were connected to the FSRs for contact forces measurements. When performing roller tasks simulation, another four channels of the converter board were connected to four strain gauges to measure the target task

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

demands. When performing tweezers or wrench simulation tasks, one channel of the converter board was connected to strain gauge dynamometer or torque sensor to measure the target force or torque demands, respectively. Three replicates of contact forces measurements were collected for each simulation. Based upon published literature, the sampling rate for FSRs applications ranged from 12 Hz to 60 Hz (Fellows and Freivalds 1989; Knudson and White 1989). For this study, the contact forces measurements were taken at a sampling frequency of 60 Hz which is within the capability of the DAS1601 converter board.

### 3.1.5 Glove Properties Measurement

The intrinsic properties used to characterize glovebox gloves are thickness, coefficients of static friction ($\mu_s$) and pliability. The nominal thicknesses of the gloves were provided by the vendor which had also been measured in the laboratory to fall within the acceptable variations specified in guidelines for gloveboxes (AGS-G001) by American Glovebox Society. The inclined plane method (ASTM G115-93) was used to measure the coefficient of static friction of glovebox gloves on aluminum surface of a 15.5 cm * 7.0 cm * 1.2 cm aluminum plate and a folding force meter designed in the laboratory was used to measure the pliability (in gram force). Both methods were used by Batra et al. (1994) and can be easily adopted in the field for glove properties measurements at low cost.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

#### 3.1.5.1 Coefficients of Static Friction

The coefficient of static friction is the ratio of tangential force and the normal force just prior to the moment of slip. A piece of glove material was mounted to a polycarbonate plate (dimensions 4.1 cm * 3.5 cm * 0.6 cm) and a 200 gram weight was attached on top of the plate. The polycarbonate plate was placed on an inclined plane with aluminum plate attached to it (Figure 14). Then, the plane was raised slowly until the plate began to slide and the sliding angle was measured using a protractor (Northern tool company, Empire Magnetic Polycast Protractor) attached onto the inclined plane. The tangent of the sliding angle was recorded as coefficient of static friction of that glove material.

**Figure 14 An inclined plane for measuring coefficients of static friction of glove materials**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 3.1.5.2 Pliability

Pliability is the property of being easily bent without breaking or cracking. A fabricated folding force meter (Figure 15) was used to measure the pliability. This force meter included an Accu force gauge with a piece of 4.1 cm (1.6") * 3.5 cm (1.4") * 0.6 cm (0.2") polycarbonate plate attached on the bottom. A handle was used to press the meter on top of a 4.1 cm (1.6") * 6.9 cm (2.7") piece of glove material until this piece of material was folded into a 4.1 cm (1.6") * 3.5 (1.4") cm piece with double thickness. This piece of glove material was taped on the inside bottom of a 4.1 cm (1.6") * 3.5 cm (1.4") * 3.5 cm (1.4") container made of polycarbonate plates where two sides of the walls were left open. The weight of the force required for folding the glove material to double thickness was recorded as pliability of that glove material.

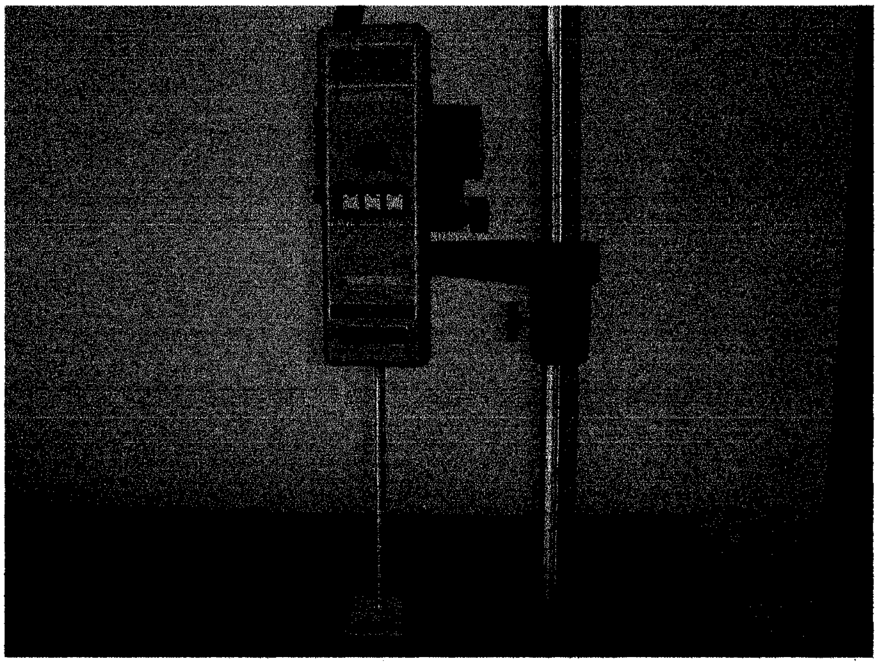


**Figure 15 A folding force meter for measuring pliability of glove materials**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 3.1.6 Experimental Design and Statistical Analysis

The dependent variables are maximum grip strength, maximum key pinch strength, and the contact forces on the palmar skin of the dominant hand. This study evaluated (1) the effect of glove on maximum grip strength and maximum key pinch strength, (2) the effects of glove and task demand on the contact forces, (3) the effects of glove material, thickness, and layer on maximum grip strength and maximum key pinch strength, and (4) the effects of glove material, thickness, layer, and task demand on the contact forces. Glove had seven levels: bare hand, 0.015" butyl (B15), 0.03" butyl (B30), 0.015" hypalon (H15), 0.03" hypalon (H30), 0.015" neoprene (N15), and 0.03" neoprene (N30). The task demand had three levels for each tool. Glove material had three levels: butyl, hypalon, and neoprene. Thickness had two levels, 0.015" and 0.03". Layer had three levels: single, double, and triple. For grip and key pinch strength, the average of three trials of each test was used in data analysis to improve the test-retest reliability (Rock et al. 2001; Mathiowetz et al. 1985). The raw data of the remaining dependent variables were used in data analysis.

Separate analyses of variance (ANOVAs) with repeated measures were used to determine whether there were significant differences between independent variables on dependent variables (Olsen 2003). Prior to the use of the repeated-measures ANOVA, the Kolmogorov-Smirnov (KS) and Levene tests were used to check the normality and homogeneity of variance of the data (Figure 16). If either (or both) of the tests was found statistically significantly at $p<0.05$ (rejecting null hypothesis of normal distribution and/or equal error variance), data transformation were performed using

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

logarithmic base 10 ($\log_{10}$) and square root functions. The transformed data were then subjected to the Kolmogorov-Smirnov and Levene tests. If both tests were passed, a repeated-measured ANOVA was carried on the transformed data. If either (or both) of the tests was found statistically significant on the transformed data, then, the nonparametric Wilcoxon signed-rank test was used for 2 related sample test and the Friedman test was used for 3 or more related samples test on the original data (without transformation). Bonferroni post hoc analyses were performed to determine which pairs of means were significantly different. In addition, a paired-samples t test (for correlated data) was used to compare whether the means of contact forces at the tip of the thumb and the tip of the index finger differed from one another during the tweezers tasks simulation.

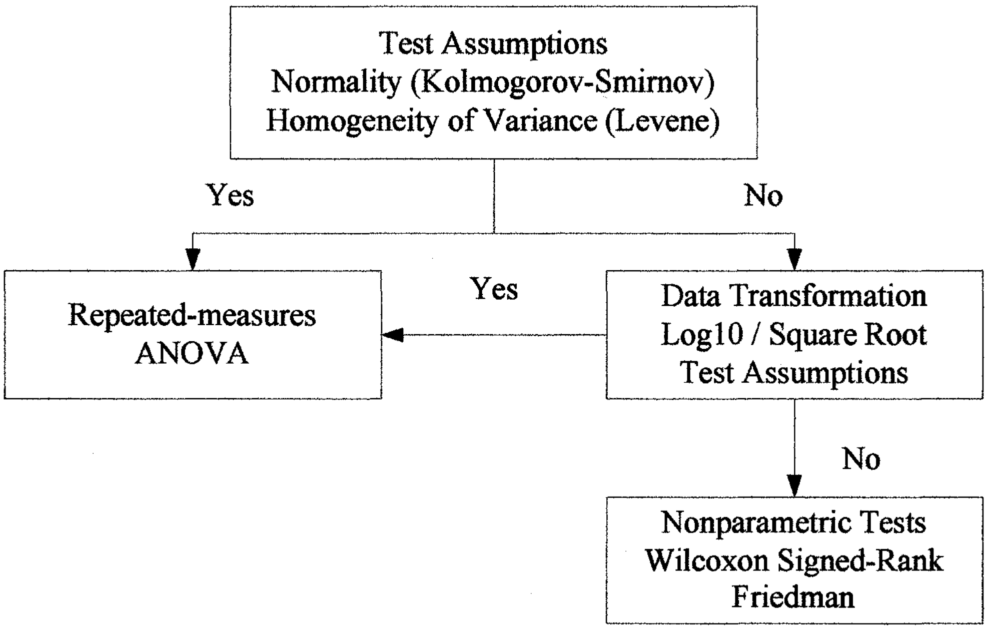


**Figure 16 Statistical Analysis Testing Procedure**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The Kolmogrov-Smirnoff test was used to check if each of the anthropometric measurements is normally distributed. This test was chosen because it is suitable for continuous distributions. The linear associations were studied between different anthropometric measurements including height and hand length vs. length of fingers and thumb using Pearson's correlation procedures. Correlation analyses were also performed to measure the strength of the linear associations between glove properties (thickness, coefficients of friction, and pliability) and hand performance (maximum grip and key pinch strength) and mechanical stress (contact forces) on the palmar skin. In addition, multiple regression analysis was performed to develop equations to predict hand performance and mechanical stress over the range of glove properties measured with the found significant factors.

All data were analyzed for statistical significance at $p \leq 0.05$ using the SPSS 8.0 (SPSS Inc, Chicago, Illinois) statistical software.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## 3.2 Evaluate the Subjective Effects on Hand Performance

Glove design and selection criteria should also based on the user's subjective evaluation of the gloves (Riley and Cochran, 1988). This specific aim was carried out to compare the subjective effects of bare and gloved hands on tactility, tingling sensation, and comfort. In addition, user preference among the seven glove conditions (bare hand and six glovebox gloves) after the completion of all the simulating tasks were ranked by the subjects and recorded.

### 3.2.1 Procedure

Following are the methods and procedures for measuring tactility, tingling, comfort and preference.

#### 3.2.1.1 Tactility Test

The static two-point discrimination test (2PD test, Morberg 1990) has long been used to evaluate a subject's ability to recognize objects that are touched or held by the hand and to assess tactile sensory impairment. To test the effect of glove usage on tactility, the subjects first performed the tip pinch exertions (Figure 17) with 2.5 lb (11 Newton) force repeatedly (12 times/minute) for 15 minutes with bare hand or gloved hands. Then, a disk-criminator (Figure 18, Kom Kare company, Middletown, Ohio) was used to perform the static 2PD test on the volar pad of subject's dominant index finger right after the completion of the tip pinch task with the subject's vision occluded and the hand supported securely to avoid movement. Testing began with a 5-mm distance

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

between the points and increased or decreased depending on the subject's response. The subject was instructed to report "one" if she felt one point and "two" if two were felt. Seven of 10 accurate responses were required to record the level of sensibility. The smallest spacing that the subject is able to differentiate one stimulus from two is recorded as the two-point discrimination (tactility). The level of sensibility of bare hand without performing the tip pinch task was also measured and served as the baseline value. A forty-five minutes break was mandated between 15 minutes tip pinch tasks.

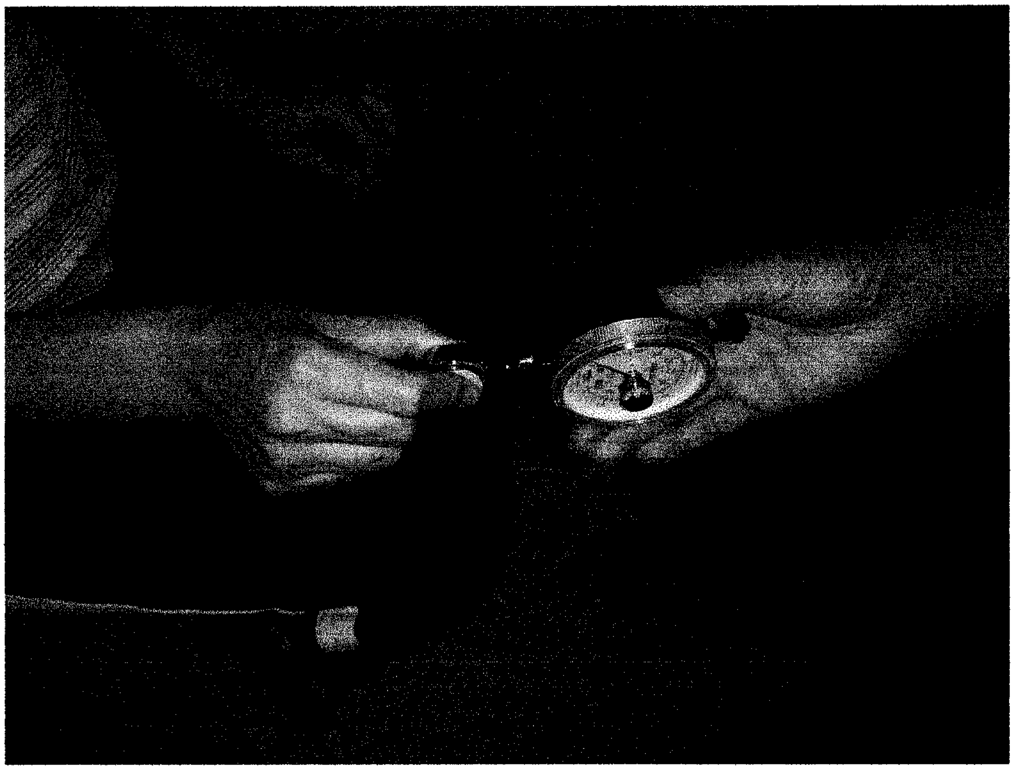


**Figure 17 Tip pinch exertions for tactility, comfort, and tingling tests using a Jamar pinch gauge**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

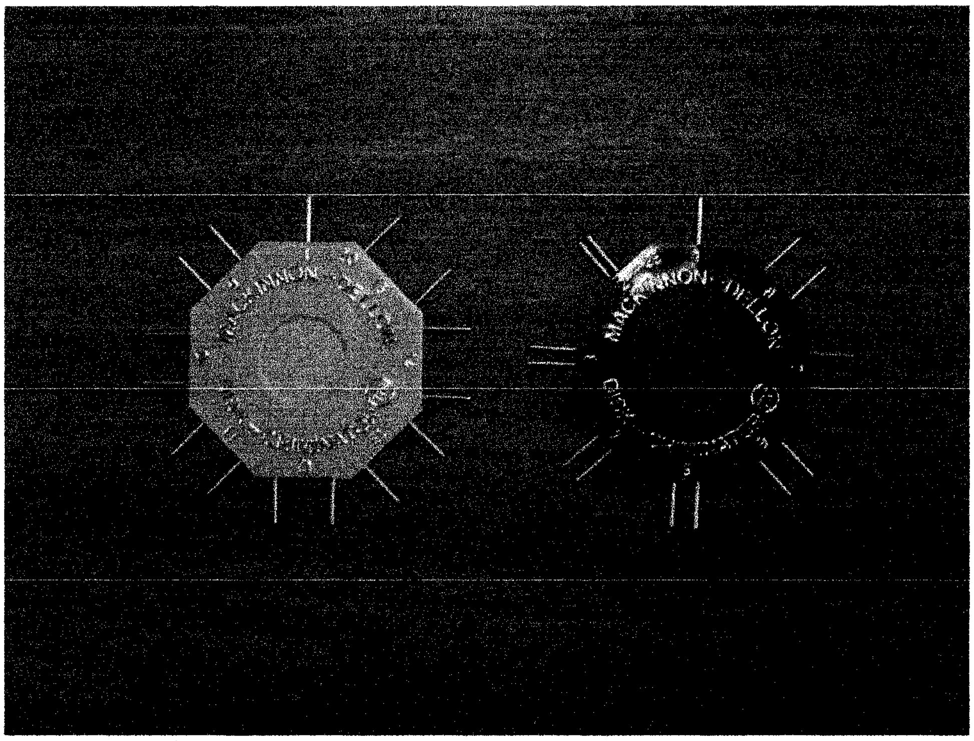


Figure 18 Disk-criminator for the tactility test

### 3.2.1.2 Tingling

Tingling is one of the subjective diagnostic criteria for Carpal Tunnel Syndrome (Gross, 1988; Rossier and Blair, 1984). This study compared the subjective effects of glovebox gloves on tingling sensation for the 15 minute tip pinch exertions using the Borg CR-10 scale (Borg 1990, shown in Table 2). Borg CR-10 scale is a psychophysical ratio scale to assess subjective symptoms, annoyances, and complaints. Ten implies extremely strong perceptual intensity. The absolute maximum is placed somewhat higher. The subjects were asked at the end of the test to give a numeric score of tingling

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

for each glove. The instructions (Appendix 3) to each subject for using the Borg CR-10 scale were given to each subject by the investigator before the tip pinch test started.

### 3.2.1.3 Comfort

Discomfort has been cited indirectly as a potential contributor to cumulative trauma disorders (Armstrong, 1986; Putz-Anderson, 1988). This study compared the subjective effects of glovebox gloves on comfort during tip pinch exertions using the Borg CR-10 scale. The subjects were asked at the end of the test to give a numeric score of discomfort for performing the tip pinch task under different glove conditions. The same instructions (Appendix 2) for using Borg CR-10 scale were given to each subject by the investigator before the tip pinch test started.

**Table 2 Borg CR-10 scale**

| **Borg CR-10 scale** | | |
|---|---|---|
| 0 | Nothing at all | |
| 0.5 | Extremely weak | (just noticeable) |
| 1 | Very weak | |
| 2 | Weak | (light) |
| 3 | Moderate | |
| 4 | | |
| 5 | Strong | (heavy) |
| 6 | | |
| 7 | Very strong | |
| 8 | | |
| 9 | | |
| 10 | Extremely strong | (almost max) |
| *Maximal | | |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

#### 3.2.1.4 Preference

To assess which glovebox gloves the subjects preferred to use for the tools simulating tasks, the subjects were asked at the completion of all simulation tasks to rank the preference among the seven glove conditions (bare hand and six glovebox gloves) and give a numeric score from 1 (most preferred) to 7 (least preferred) for each glove condition.

### 3.2.2 Experimental Design and Statistical Analysis

The dependent variables are tactility, tingling, comfort, and preference. This study evaluated (1) the effect of glove on each of the dependent variable and (2) the effects of glove material and thickness on each of the dependent variable. Glove had seven levels: bare hand, 0.015" butyl, 0.03" butyl, 0.015" hypalon, 0.03" hypalon, 0.015" neoprene, and 0.03" neoprene. Glove material had three levels: butyl, hypalon, and neoprene. Thickness had two levels, 0.015" and 0.03". Repeated-measures ANOVA or nonparametric (Wilcoxon signed-rank or Friedman) test were performed on the collected data based on the criteria stated in "Experimental Design and Statistical Analysis" section of specific aim 1. All data were analyzed for statistical significance at $p \leq 0.05$ using the SPSS 8.0 (SPSS Inc, Chicago, Illinois) statistical software.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## 3.3 Estimate the Tendon and Muscle Forces of Thumb and Fingers Using a Biomechanical Model

This section introduces and selects the biomechanical model and describes the computer program used to estimate the tendon and muscle forces.

### 3.3.1 Biomechanical Model

Effects of gloves on tendons and muscles strain were also included in developing ergonomics guidelines for glovebox gloves. Assessment of tendons and muscles forces can better the understanding of hand function and can be used to evaluate mechanical causes for hand pathologies associated with the use of hand tools. In addition, it can help physicians plan the best recovery of mechanical function of an injured hand.

Biomechanical models of the hand have been used to study different aspects of the normal and abnormal behavior of the hand in terms of motion and force production for prehension. Because of the complexity of the hand, most models were developed for individual digits and not for the whole hands. A biomechanical model that encompasses all aspects of hand function is not yet available due to the versatility of the hand. For force analysis, biomechanical models have been used to calculate two-dimensional (2D) and three-dimensional (3D) tendon and muscle forces production with measured external forces of single and multiple fingers. Since the human hand is a three-dimensional structure and the tasks performed in this study may require 3D force exertions, 3D models used to estimate tendons and muscles forces were considered in this study.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

For 3D force analysis, Chao et al. (1976) determined 3D constraint forces of the finger tendons and joints for index, middle, and little fingers in four basic isometric hand functions (tip pinch, lateral pinch, ulnar pinch and grasp). Cooney and Chao (1977) calculated the internal forces in the joints and soft tissues of the thumb during pinch and grasp functions. An et al. (1979) estimated tendon and muscle forces for four fingers in four basic isometric hand functions (tip pinch, lateral pinch, ulnar pinch and grasp). An et al. (1985) refined the model developed by Chao et al. (1976) by examining additional objective functions for solutions using the optimization methods. Chao et al. (1989) refined An et al.'s (1979) model by adding the coefficient of force and moment potential for the thumb to estimate the tendons and muscles forces for the thumb in addition to the four fingers.

Chao et al.'s (1989) 3D biomechanical model was adopted in the present study to estimate tendon and muscle forces for fingers and thumb. This model was chosen due to the following reasons 1) it is a 3D biomechanical model; 2) it involves all the fingers and the thumb; 3) it includes four basic isometric hand functions (tip pinch, lateral pinch, ulnar pinch and grasp in Figure 19) which are related to the tasks of this study.

Chao et al.'s model used ten fresh cadaver specimens to determine the three-dimensional locations of tendons with respect to the bony segments at the joints. The tendons and muscles involved in the hand functions are listed in Table 3. Six Cartesian coordinate systems were established to define the locations and orientation of tendons. There are two coordinate systems for both the middle and proximal phalanges and only one system for both the distal phalanx and metacarpal. The x-axis is projected along the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

phalangeal or the metacarpal shaft, passing from the center of rotation to the center of the concave articular surface at the proximal end. The y-axis is projected dorsally, and the z-axis is projected radially for the right hand and ulnarly for the left hand. Two parameters, "force potential' and "moment potential", were determined from raw data to describe the orientation and location of each tendon. The force potential is expressed in terms of the directional cosine of a tendon with respect to the distal system. It provides the contribution of a particular tendon in generating joint constraint forces. The moment potential specifies the moment arm of the tendon in regard to the joint center and in the direction of each coordinate axis of the distal system. It specifies the functional moment of each tendon in rotating the joint at three mutually perpendicular directions. The mean value of these parameters among the 10 specimens was then used to construct the normative model. Following are the forms of equilibrium equations at the distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint, and metacarpophalangeal (MP) joint for the fingers and the interphalangeal (IP) joint, metacarpophalangeal joint (MP), and the carpometacarpal (CMC) joint for the thumb:

Force equations

$$\begin{aligned} &\Sigma\ \alpha_i F_i + C_x + R_x = 0 \\ &\Sigma\ \beta_i F_i + C_y + R_y = 0 \\ &\Sigma\ \gamma_i F_i + C_z + R_z = 0 \end{aligned} \tag{4}$$

Moment equations

$$\Sigma\ a_i F_i + M_x + T_x = 0$$

$$\Sigma\ b_i F_i + M_y + T_y = 0 \tag{5}$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$$\Sigma\ c_iF_i + M_z + T_z = 0$$

where

$\alpha_i, \beta_i, \gamma_i$ = force potential parameters,

$a_i, b_i, c_i$ = moment potential parameters,

$C_x, C_y, C_z$ = unknown joint constraint forces,

$M_x, M_y, M_z$ = unknown joint constraint moments,

$F_i$ = unknown tendon or muscle forces,

$R_x, R_y, R_z$ = externally applied forces, and

$T_x, T_y, T_z$ = externally applied moments.

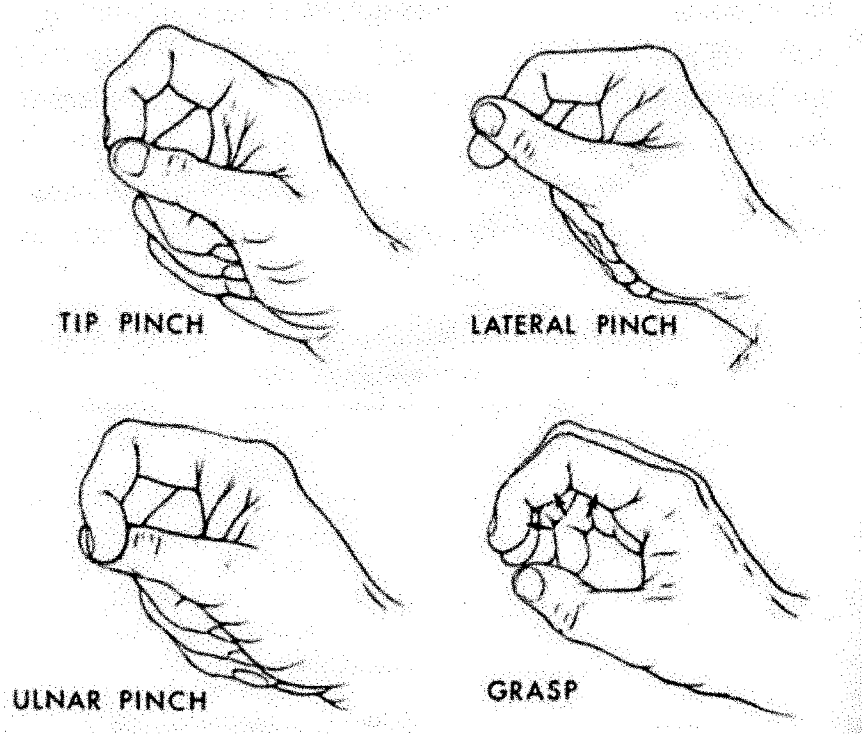


**Figure 19 Four basic isometric hand functions**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Table 3 Tendons and muscles involved in hand function**

| Hand element | Joint | Tendons and muscles |
|---|---|---|
| Finger | DIP | Terminal extensor (TE) |
| | | Flexor profundus (FP) |
| | PIP | Extensor slip (ES) |
| | | Radial band (RB) |
| | | Ulnar band (UB) |
| | | Flexor sublimes (FS) |
| | MP | Long extensor (LE) |
| | | Radial interosseous (RI) |
| | | Ulnar interosseous (UI) |
| | | Lumbrical (LU) |
| Thumb | IP | Flexor pollicis longus (FPL) |
| | | Extensor pollicis longus (EPL) |
| | MCP | Abductor pollicis brevis (APB) |
| | | Flexor pollicis brevis (FPB) |
| | | Adductor pollicis (ADD) |
| | | Extensor pollicis brevis (EPB) |
| | CMC | Opponens pollicis (OPP) |
| | | Abductor pollicis longus (APL) |

The required input parameters for using this model are externally applied force (s) and the flexion-extension ($\Phi$), radioulnar deviation ($\theta$), and pronation-supination ($\psi$) angles of the DIP, PIP, and the MP joints of the fingers and the IP and MP joints of the thumb. The expected outcomes determined using Chao et al.'s static force analysis are the unknown tendon forces and joint constraint forces and moments.

The externally applied forces were the contact forces measured in aims 1 of this study. An angle gauge was used to measure the flexion-extension angles at the DIP, PIP and the MP joints of the fingers and the IP and MP joints of the thumb when holding the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

tools in static mode since no angle gauge was available in the market to measure the angles during tasks simulation. The radioulnar deviations and pronation-supination angles were not measured and assumed to be 0 since the hand as in neutral positions (An et al. 1985) for those two planes when performing the simulating tasks.

When fingers and thumb were in the functional configuration other than the neutral position, the following coordinate transformation equation was performed so that the tendon and the externally applied forces could be defined in the same coordinate system for the force analysis.

$$\begin{bmatrix} X_D \\ Y_D \\ Z_D \end{bmatrix} = \begin{bmatrix} c\theta c\phi & c\theta s\phi & -s\theta \\ -c\psi s\phi + s\psi s\theta c\phi & c\psi c\phi + s\psi s\theta s\phi & s\psi c\theta \\ s\psi s\phi + c\psi s\theta s\phi & -s\psi c\phi + c\psi s\theta s\phi & c\psi c\theta \end{bmatrix} \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \tag{6}$$

in which,

$X_D$, $Y_D$, $Z_D$ = coordinate of a tendon point or components of a vector measured with respect to the distal system,

$X_P$, $Y_P$, $Z_P$ = coordinate of a tendon point or components of a vector measured with respect to the proximal system,

$X_0$, $Y_0$, $Z_0$ = coordinate of the origin of the proximal system expressed in the distal system,

s = sine, and

c = cosine.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

When free-body analyses were performed on the thumb joints, there are a total of 21 unknowns including 8 unknown tendon forces, 9 unknown constraint forces, and 4 unknown moments with 9 force equilibrium equations and 9 moment equilibrium equations available. To solve the unknown, two assumptions (Cooney and Chao 1977) were made to reduce the unknowns to make the problems statistically determinate. The first assumption is that the extensor pollicis longus and extensor pollicis brevis tendons were eliminated from consideration since they act in the same direction as the applied force and carry a minimum load. The second assumption is that the flexor brevis and opponens pollicis muscles were assumed to act as one force vector, primarily at the carpometacarpal joint. Then, one possible admissible solution can be produced for the 18 remaining unknowns (5 tendons forces, 9 constraints forces, and 4 unknown moments) by using the 18 equilibrium equations.

When free-body analyses were performed on all three finger joints, there were a total of 19 independent equations including 9 force equations and 9 moment equations as mentioned above and one constraint equation. The constraint equation is that the calculated force of terminal extensor equals the sum of the calculated forces of radial and ulnar bands. The total unknown joint-constraint forces and moments (14) and tendon forces (9) were 23. Based on a systematic combination, any four of the nine tendons were assumed to be zero, thus making the system statistically determinate. A total of 126 possible combinations of unknown were resolved uniquely. Among these combinations, the following constraint conditions (Chao et al. 1975) were used to find and discard the inadmissible solutions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1 any of the tendons bear compressive forces,

2 any of the joint axial compressive forces become tensile, and

3 any of the results reach unreasonably large magnitudes in pinch or grasp.

When applying this model, the linkage length are all normalized with respect to the distances between the center of rotation of DIP joint and the center of the concave surface of the PIP joint of the corresponding finger to avoid anthropometric variations.

### 3.3.2 Computer Program

A computer program (see Appendix 4 for the programming code) written and compiled using Microsoft Visual Basic, Version 6.0 was used to solve the simultaneous equations for thumb and fingers by Gaussian elimination method.

When the program is initiated, the user was asked first to pick the thumb or one of the four fingers from a combo box. Then, the user needs to click on the "solve system" command box to calculate admissible solutions. There are three main sub functions inside this computer program. The "Build Matrix" sub function is used to build the [A] and {B} matrices of the linear system [A]*{x} = {B}. The force and moment potential coefficients in matrix A and external applied forces and moments in matrix B were pre-entered in a Microsoft Excel file. Inside the Excel file, the user also needed to enter the contact force, flexion-extension angles at the DIP, PIP, and MP joints of the finger or the IP and MP joints of the thumb, linkage length, and finger-tool contact orientation information. Then, this Excel file performed the necessary coordinate

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

transformation of externally applied contact forces using the equation (3) provided previously.

The "Build Triangular Matrix" sub function is going to build a triangular matrix from the matrix [A]. This sub function will first compose the augmented matrix in the following form.

$$\left[\begin{array}{cccc|c} a_{11} & a_{12} & \dots & a_{1k} & b_1 \\ a_{21} & a_{22} & \dots & a_{2k} & b_2 \\ \dots & \dots & \dots & \dots & \dots \\ a_{k1} & a_{k2} & \dots & a_{kk} & b_k \end{array}\right]$$

Then, this sub function performs elementary row operations to put the augmented matrix into the following upper triangular form.

$$\left[\begin{array}{cccc|c} a'_{11} & a'_{12} & \dots & a'_{1k} & b'_1 \\ 0 & a'_{22} & \dots & a'_{2k} & b'_2 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & a'_{kk} & b'_k \end{array}\right]$$

The third main sub function "Back Substitution" solves the equation of the $k_{th}$ row for $x_k$ first, then substitutes back into the equation of the $(k-1)_{st}$ row to obtain a solution for $x_{k-1}$, etc., according to the following formula to calculate the solution array {x}using the back substitution method.

$$xi = \frac{1}{a'ii}\left(b'i - \sum_{j=i+1}^{k} a'ijxj\right)$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

For the fingers, another sub function “Validity Check” was also used to apply the constraint conditions to discard the inadmissible solutions after all the solutions were calculated. Finally, the admissible solutions of the tendon forces were sent to another Excel file for further data analysis.

This software implements the methodology of Gaussian elimination step by step in computer code and has the ability to perform the biomechanical analysis of static forces in the thumb and fingers during normal hand functions. The interface is also user friendly and completely event driven.

### 3.3.3 Experimental Design and Statistical Analysis

The dependent variables are the predicted tendon and muscle forces. This study evaluated (1) the effects of glove and task demand on the predicted tendon and muscle forces and (2) the effects of glove material, thickness, layer, and task demand on the contact forces. Glove had seven levels: bare hand, 0.015” butyl, 0.03” butyl, 0.015” hypalon, 0.03” hypalon, 0.015” neoprene, and 0.03” neoprene. The task demand had three levels for each tool. Glove material had three levels: butyl, hypalon, and neoprene. Thickness had two levels, 0.015” and 0.03”. Layer had three levels: single, double, and triple. The average of three trials of each test was used in data analysis to improve the test-retest reliability (Rock et al. 2001; Mathiowetz et al. 1985). Repeated-measures ANOVA or nonparametric (Wilcoxon signed-rank or Friedman) test was performed on the predicted data based on the criteria stated in “Experimental Design and Statistical

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Analysis" section of specific aim 1. All data were analyzed for statistical significance at $p \leq 0.05$ using the SPSS 8.0 (SPSS Inc, Chicago, Illinois) statistical software.

### 3.4 Formulate Ergonomics Design/Selection Guidelines

Personal protective gloves are designed to satisfy user performance, safety and health needs, and to meet regulatory requirements (Riley and Cochran, 1988). The design factors include materials availability, task requirements, environment (e.g. extreme temperature), and conditions of use (e.g. field versus laboratory) (Muralidhar et al. 1999). To established design criteria for gloves, hazard evaluation should be performed first to identify the character and extent of physical (including radioactive), chemical, and biological hazards present. Then, ergonomic factors (e.g. hand anthropometry) and other requirements (e.g. storage requirements) should also be considered. Based on these, the design criteria for desired hand protection can be determined for the gloves.

This study recommended the ergonomics design and selection guidelines of glovebox gloves to optimize protection without compromising hand performance. The guidelines address the following two issues:

1. Minimize effects of glovebox gloves on hand performance

To minimize effects on hand performance, tingling sensation and discomfort need to be minimized, and good tactile perception, maximum grip strength, and maximum key pinch strength need to be maintained. The results of objective and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

subjective effects of glovebox gloves on hand performance were used to determine the glove material (s), thickness, and number of layers that should be included in the design/selection guidelines to minimize the effects on hand performance. In addition, glove properties and their interactions were determined by stepwise regression to predict maximum grip strength, maximum key pinch strength, and contact force on the palmar skin.

2. Optimize protection

To optimize protection, the hand and glove/tools contact areas that are subject to high mechanical stress should be minimized (Fraser 1980). In addition, the additional strain posed by the use of gloves on both the tendons and muscles of the hand should also be and minimized (Hallbeck et al. 1995). The results of effects of glovebox gloves on contact forces and muscle and tendon forces were used to identify the glove material (s), thickness, and number of layers to minimize the mechanical stress on the palmar skin and on the tendons and muscles of the fingers and the thumb.

Following these two issues, the design and selection guidelines established could consist of best glove material, best thickness, and best gloving condition to satisfy user performance and accomplish safety and health needs for the desired hand protection.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# Chapter 4

## Results

This chapter reports the following results: (1) anthropometry of eleven female subjects, (2) calibration of sensors, (3) effect on grip and key pinch strength, (4) effects on contact forces, (4) effects of properties of glove material, (5) effect on subjective hand performance, and (6) effect on tendon and muscle forces.

### 4.1 Anthropometric Data

Table 4 lists the means and standard deviations of 20 hand dimensions and height, weight, and age of the eleven participating female subjects. It is frequently assumed among designer that anthropometric dimensions are normally distributed (Vaus and Mital, 2000). The Kolmogrov-Smirnoff test results (Table 4) shows that the Asymptotic Significance (2-tailed) is greater than 0.05 for each of the anthropometric measurement. It is interesting to note that all the anthropometric dimensions measured in the present study are normally distributed even for this small sample size.

The linear relationships of height and length of hand with length of thumb and fingers were investigated. Table 5 shows of Pearson's correlations coefficients between these variables. The correlation coefficients between height and length of index finger display significant positive value (0.67). It is worthy to note that significant positive correlations with values between 0.70 and 0.91 were found between length of hand and length of fingers. No significant correlation was found between height and length of hand.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Table 4 Mean and standard deviations for anthropometry data of the eleven female subjects**

| Description | Mean (mm) | SD | KS* |
|---|---|---|---|
| **1. Finger tip to root digit 5** | 51.5 | 3.0 | 0.76 |
| **2. Finger tip to root digit 3** | 71.0 | 2.9 | 0.85 |
| **3. 1st joint to root digit 5** | 29.4 | 2.4 | 0.87 |
| **4. 1st joint to root digit 3** | 46.8 | 3.0 | 0.72 |
| **5. 2nd joint to root digit 5** | 16.6 | 1.3 | 0.89 |
| **6. 2nd joint to root digit 3** | 24.4 | 2.0 | 0.99 |
| **7. Depth at tip digit 5** | 10.4 | 0.7 | 0.66 |
| **8. Depth at tip digit 3** | 12.3 | 0.6 | 0.98 |
| **9. Breadth at first joint digit 5** | 13.0 | 1.2 | 0.99 |
| **10. Breadth at first joint digit 3** | 15.2 | 0.9 | 1.00 |
| **11. Breadth at second joint digit 5** | 14.8 | 1.0 | 0.97 |
| **12. Breadth at second joint digit 3** | 17.2 | 0.9 | 1.00 |
| **13. Finger tip to knuckle thumb** | 56.4 | 2.8 | 0.91 |
| **14. Breadth at knuckles** | 69.0 | 3.5 | 0.81 |
| **15. Maximum breadth of hand** | 87.2 | 3.8 | 0.97 |
| **16. Length of hand** | 167.0 | 5.1 | 1.00 |
| **17. Depths at knuckles** | 27.1 | 2.3 | 0.78 |
| **18. Circumference of hand** | 205.5 | 11.2 | 0.62 |
| **19. Height (cm)** | 159.7 | 5.0 | 0.99 |
| **20. Age (yrs)** | 32 | 5 | 0.80 |
| **21. Weight (kg)** | 51.5 | 6.3 | 0.91 |
| **22. Fingertip to root digit 2** | 64.0 | 2.6 | 0.92 |
| **23. Fingertip to root digit 4** | 65.8 | 2.5 | 0.99 |

* KS: Kolmogrov-Smirnoff Asymptotic Significance

## 4.2 Calibration of Force Sensing Resistor, Strain Gauge, and Torque Sensor

Figure 20 shows a typical calibration line of a FSR with $R^2$ value of 0.997 ($p < 0.001$). Figures 21 and 22 show the calibration lines for strain gauge and torque sensor with $R^2$ values of 0.9999 ($p < 0.0001$) and 0.9997 ($p < 0.0001$), respectively. The useful ranges of FSRs, strain gauges, and torque sensor ranged from 0 to 44.5 N, 0 to 22.2 N, and 0 to 10.2 Newton-meter, respectively.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Table 5 Correlation Coefficients of length of thumb and fingers with height and length of hand for eleven female subjects**

| | Height | Length of hand |
|---|---|---|
| **Length of hand** | 0.54 | --- |
| **Finger tip to knuckle thumb** | 0.24 | 0.49 |
| **Fingertip to root digit 2** | 0.67* | 0.90** |
| **Finger tip to root digit 3** | 0.41 | 0.91** |
| **Fingertip to root digit 4** | 0.20 | 0.70* |
| **Finger tip to root digit 5** | 0.48 | 0.72* |

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

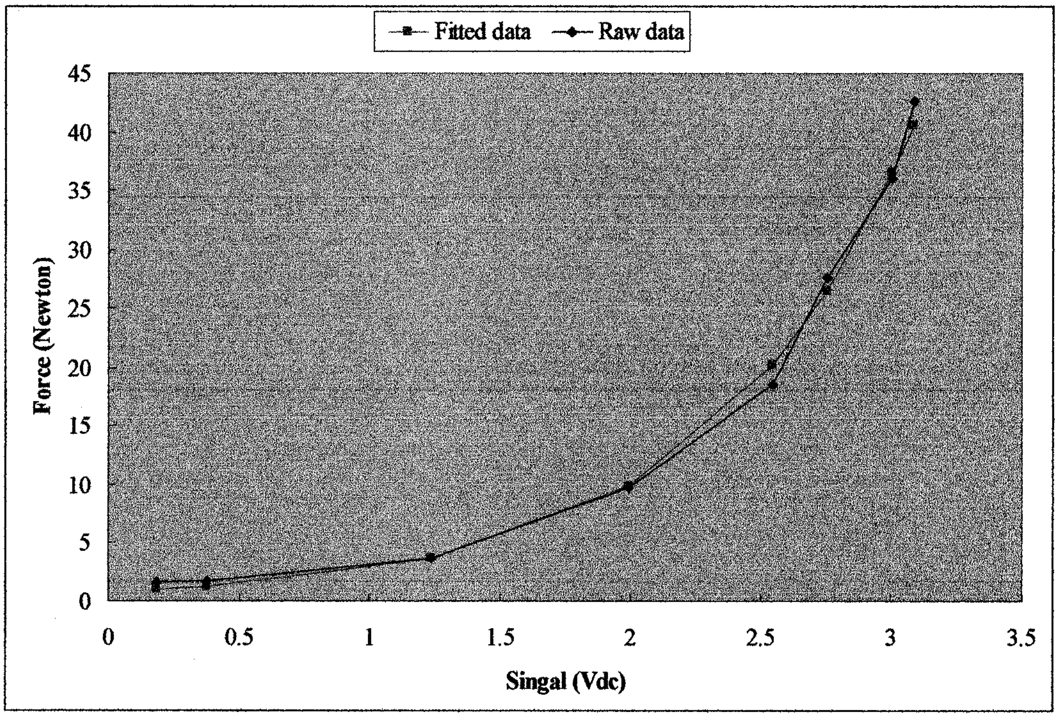


**Figure 20 Calibration of the force sensing resistor**

**Force (Newton) = 0.378 * EXP(1.291 * Signal (Vdc)) + 0.378 * EXP(1.291 * Signal (Vdc)), $R^2 = 0.997$, $p$-value < 0.001**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

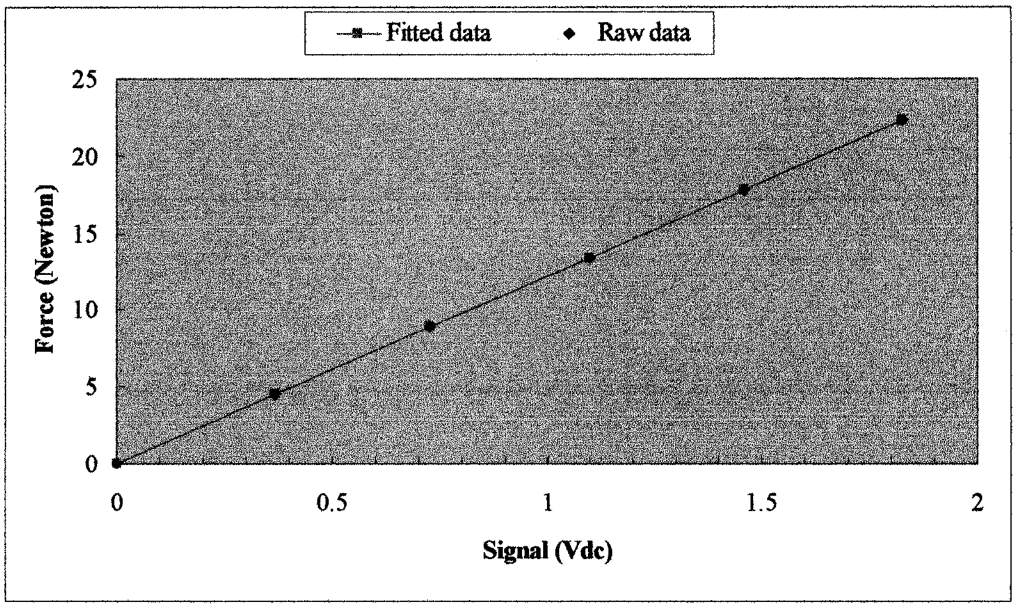


**Figure 21 Calibration of the strain gauge**

**Force (Newton) = 12.19 * Signal (Vdc), $R^2$ = 0.9999, p-value < 0.0001**

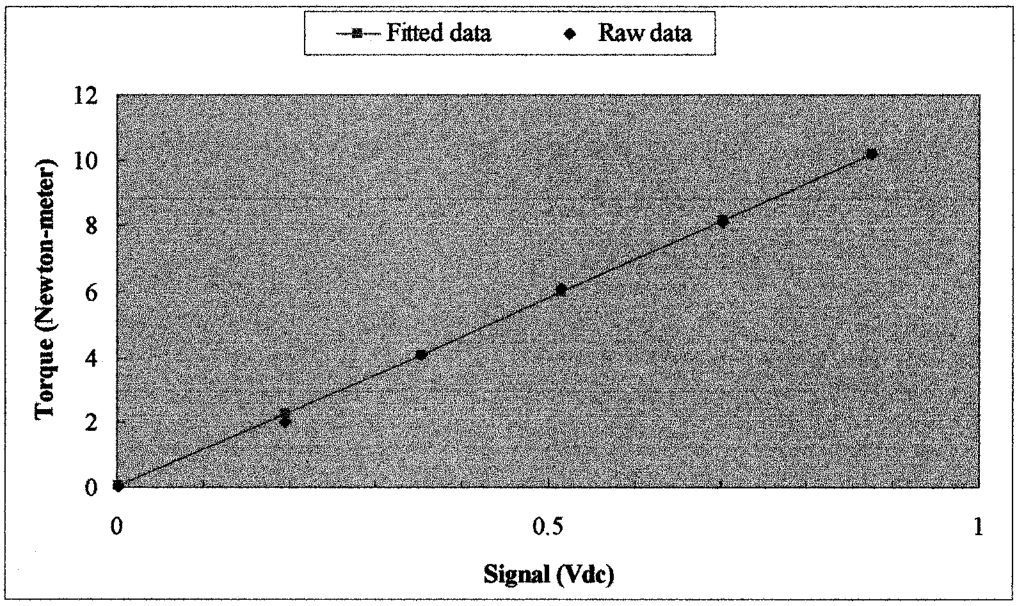


**Figure 22 Calibration of the torque sensor**

**Torque (Newton-meter) = 11.61 * Signal (Vdc), $R^2$ = 0.9998, p-value < 0.0001**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 4.3 Effects on Grip Strength

Table 6 shows the means and standard deviations of the maximum grip strength estimated for different glove material, thickness, and layer condition for the eleven female subjects. The amount of reduction for maximum grip strength for gloved hands compared to bare hand ranges from 8.8% to 37.8% in this study.

**Table 6 Maximum grip strength and percent reduction compared to bare hand for eleven female subjects**

| Glove Material | Thickness (inch) | Layer | Grip strength (kg) Mean | SD | % Reduction |
|---|---|---|---|---|---|
| Bare | --- | --- | 25.9 | 2.4 | --- |
| Butyl | 0.015 | Single | 23.6 | 1.3 | 8.8 |
| Butyl | 0.015 | Double | 21.1 | 1.5 | 18.7 |
| Butyl | 0.015 | Triple | 19.7 | 1.4 | 25.2 |
| Butyl | 0.030 | Single | 21.6 | 1.7 | 16.4 |
| Butyl | 0.030 | Double | 19.3 | 1.8 | 25.4 |
| Butyl | 0.030 | Triple | 18.3 | 1.3 | 29.4 |
| Hypalon | 0.015 | Single | 23.6 | 1.4 | 8.8 |
| Hypalon | 0.015 | Double | 20.8 | 1.1 | 19.5 |
| Hypalon | 0.015 | Triple | 19.0 | 1.2 | 26.5 |
| Hypalon | 0.030 | Single | 21.0 | 1.7 | 19.0 |
| Hypalon | 0.030 | Double | 18.7 | 1.3 | 27.6 |
| Hypalon | 0.030 | Triple | 17.2 | 1.3 | 33.6 |
| Neoprene | 0.015 | Single | 23.5 | 1.5 | 9.1 |
| Neoprene | 0.015 | Double | 20.8 | 1.2 | 19.8 |
| Neoprene | 0.015 | Triple | 19.2 | 1.7 | 25.8 |
| Neoprene | 0.030 | Single | 20.0 | 1.3 | 22.6 |
| Neoprene | 0.030 | Double | 17.7 | 1.2 | 31.7 |
| Neoprene | 0.030 | Triple | 16.1 | 1.4 | 37.8 |

Two separate repeated-measured ANOVAs were conducted using maximum grip strength as dependent variable since the significances of both the KS and Levene tests

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

were greater than 0.05. The first repeated-measured ANVOA was used to determine whether there were significant differences between maximum grip strength in different glove conditions – bare hand, 0.015" butyl, 0.03" butyl, 0.015" hypalon, 0.03" hypalon, 0.015" neoprene, and 0.03" neoprene. The procedure rejected null hypothesis number (1) for maximum grip strength indicated that there were significant differences (F=35.88, $p<0.0001$) between glove conditions. Bonferroni post hoc analyses were used to determine which pairs of means were significantly different. The pairwise comparisons (Table 7) show that there were statistically significant differences for bare hand vs. all gloves, B15 vs. B30, H30, and N30, H15 vs. H30 and N30, H30 vs. N15, and N15 vs. N30. The results indicate that mean grip strength for all gloved hands is significantly lower than that of bare hand.

The second repeated-measured ANOVA evaluated the effects of glove material, thickness, and layer condition on the maximum grip strength. The results (Table 8) reject null hypotheses (2), (3), and (4) for maximum grip strength and show that there are significant differences between glove material (F=8.84, $p<0.005$), thickness (F=104.35, $p<0.0001$) and layer condition (F=305.45, $p<0.0001$). In addition, there is a statistically significant interaction effect (F=8.99, $p<0.005$) between glove material and thickness on the maximum grip strength. Bonferroni pairwise comparisons (Table 9) in glove material effect show that there were statistically significant differences for butyl vs neoprene and hypalon vs. neoprene. This indicates that the butyl and hypalon gloves can retain significantly higher maximum grip strength than the neoprene gloves. In layer effect, statistically significant differences were found for single vs. double, single vs.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

triple, and double vs. triple. The results show that more the layers of gloves are worn, the greater the grip strength reduction. In addition, the thinner (0.015") gloves retain significantly higher maximum grip strength (2.3 kg in mean differences) than the thicker (0.03") glove. Figure 23 shows the plot of Glove Material * Thickness interaction. For thin gloves, the grip strength seems the same for different glove materials. For thick gloves, neoprene material seems to reduce grip strength compared to butyl and hypalon materials.

**Table 7 Bonferroni post hoc tests for glove on grip strength for eleven female subjects**

| (I) Glove | (J) Glove | Mean Difference (I-J) (kg) | Std. Error | Sig. |
|---|---|---|---|---|
| Bare | B15 | 2.3 | 0.5 | 0.039 |
| | B30 | 4.3 | 0.6 | 0.001 |
| | H15 | 2.3 | 0.5 | 0.023 |
| | H30 | 4.9 | 0.7 | 0.001 |
| | N15 | 2.4 | 0.5 | 0.016 |
| | N30 | 5.8 | 0.7 | 0.000 |
| B15 | B30 | 2.0 | 0.5 | 0.040 |
| | H15 | -0.0 | 0.2 | 1.000 |
| | H30 | 2.6 | 0.5 | 0.003 |
| | N15 | 0.1 | 0.1 | 1.000 |
| | N30 | 3.6 | 0.4 | 0.000 |
| B30 | H15 | -2.0 | 0.6 | 0.163 |
| | H30 | 0.7 | 0.4 | 1.000 |
| | N15 | -1.9 | 0.5 | 0.113 |
| | N30 | 1.6 | 0.5 | 0.199 |
| H15 | H30 | 2.6 | 0.5 | 0.007 |
| | N15 | 0.1 | 0.1 | 1.000 |
| | N30 | 3.6 | 0.4 | 0.000 |
| H30 | N15 | -2.6 | 0.4 | 0.004 |
| | N30 | 0.9 | 0.2 | 0.075 |
| N15 | N30 | 3.5 | 0.4 | 0.000 |

The following glove abbreviations will be used throughout this study

| | | | | | |
|---|---|---|---|---|---|
| B15: | 0.015" butyl glove | B30: | 0.03" butyl glove | H15: | 0.015" hypalon glove |
| H30: | 0.03" hypalon glove | N15: | 0.015" neoprene glove | N30: | 0.03" neoprene glove |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Table 8 ANOVA with repeated measures results for effects of glove material, thickness, layer, and their interactions on maximum grip strength for eleven female subjects**

| Source | SS | Df | MS | F | Sig |
|---|---|---|---|---|---|
| Glove material (G) | 32.04 | 2 | 16.02 | 8.84 | 0.0018 |
| Thickness (TH) | 270.90 | 1 | 270.75 | 104.35 | 0.0000 |
| Layer (L) | 547.07 | 2 | 273.53 | 305.45 | 0.0000 |
| G * TH | 22.28 | 2 | 11.14 | 8.99 | 0.0016 |
| G * L | 1.10 | 4 | 0.28 | 0.72 | 0.5806 |
| TH * L | 3.99 | 2 | 1.99 | 2.81 | 0.0842 |
| G * TH * L | 0.70 | 4 | 0.18 | 0.41 | 0.7971 |

**Table 9 Bonferroni post hoc tests for glove material, thickness, and layer on grip strength for eleven female subjects**

| (I) Glove M | (J) Glove M | Mean Difference (I-J) (kg) | Sig. |
|---|---|---|---|
| Butyl | Hypalon | 0.5 | 0.2912 |
| | Neoprene | 1.0 | 0.0112 |
| Hypalon | Neoprene | 0.5 | 0.0349 |
| **(I) Thickness** | **(J) Thickness** | | |
| 0.015" | 0.03" | 2.3 | 0.0000 |
| **(I) Layer** | **(J) Layer** | | |
| Single | Double | 2.5 | 0.0000 |
| | Triple | 4.0 | 0.0000 |
| Double | Triple | 1.5 | 0.0000 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

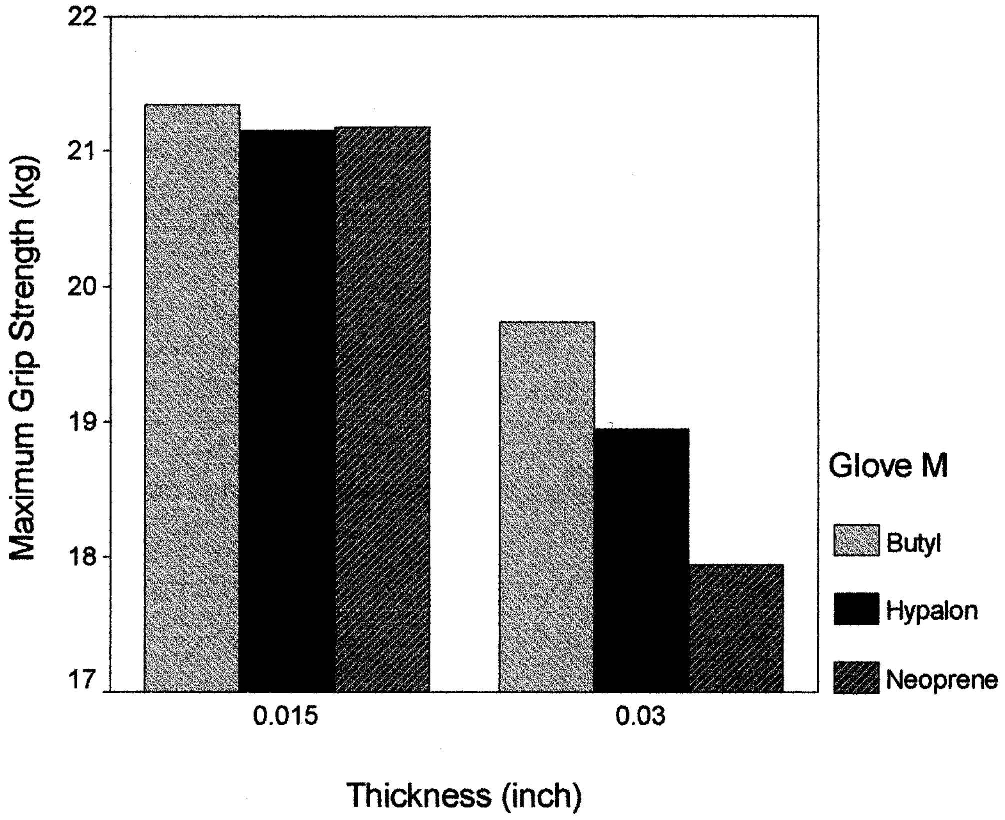


**Figure 23 Interaction of Glove Material * Thickness on maximum grip strength**

### 4.4 Effects on Key Pinch Strength

Table 10 shows the means and standard deviations of the maximum key pinch strengths estimated for different gloved hands, thickness and layer conditions for the eleven subjects. A repeated-measures ANOVA was used to evaluate the effects of glove on maximum pinch strength where the sample data passed both the normality and equal variance tests. The procedure did not reject null hypothesis (1) for maximum key pinch strength and showed no significant effect of glove on the maximum key pinch strength. To evaluate the effects of glove material, thickness and layer on maximum pinch

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

strength, all the original data (Z=2.58, Asymptotic Significance<0.05), log10 transformation data (Z=2.30, Asymptotic Significance<0.05), and square root transformation data (Z=2.43, Asymptotic Significance<0.05) did not pass the normality (Kolmogorov-Smirnov) tests. The Friedman tests did no reject null hypotheses (2) and (4) for maximum key pinch strength and showed no significant differences between glove materials and layers in maximum pinch strength where the Asymptotic Significance is great the 0.05. However, Wilcoxon signed-rank test rejects null hypothesis (3) for maximum key pinch strength and shows significant differences in thickness (Z=-5.12, Asymptotic Significance<0.05) where 0.015" thickness gloves yielded higher maximum key pinch strength than the 0.03" thickness gloves (Figure 24).

**Table 10 Maximum key pinch strength for eleven female subjects**

| Glove Material | Thickness (inch) | Layer | Key Pinch (kg) Mean | SD |
|---|---|---|---|---|
| Bare | --- | --- | 6.5 | 0.8 |
| Butyl | 0.015 | Single | 6.6 | 0.6 |
| Butyl | 0.015 | Double | 6.6 | 0.9 |
| Butyl | 0.015 | Triple | 6.4 | 0.7 |
| Butyl | 0.030 | Single | 6.4 | 0.6 |
| Butyl | 0.030 | Double | 6.3 | 0.6 |
| Butyl | 0.030 | Triple | 6.3 | 0.5 |
| Hypalon | 0.015 | Single | 6.5 | 0.7 |
| Hypalon | 0.015 | Double | 6.6 | 0.7 |
| Hypalon | 0.015 | Triple | 6.5 | 0.8 |
| Hypalon | 0.030 | Single | 6.4 | 0.7 |
| Hypalon | 0.030 | Double | 6.4 | 0.7 |
| Hypalon | 0.030 | Triple | 6.3 | 0.7 |
| Neoprene | 0.015 | Single | 6.5 | 0.7 |
| Neoprene | 0.015 | Double | 6.5 | 0.6 |
| Neoprene | 0.015 | Triple | 6.5 | 0.6 |
| Neoprene | 0.030 | Single | 6.4 | 0.7 |
| Neoprene | 0.030 | Double | 6.5 | 0.7 |
| Neoprene | 0.030 | Triple | 6.3 | 0.7 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

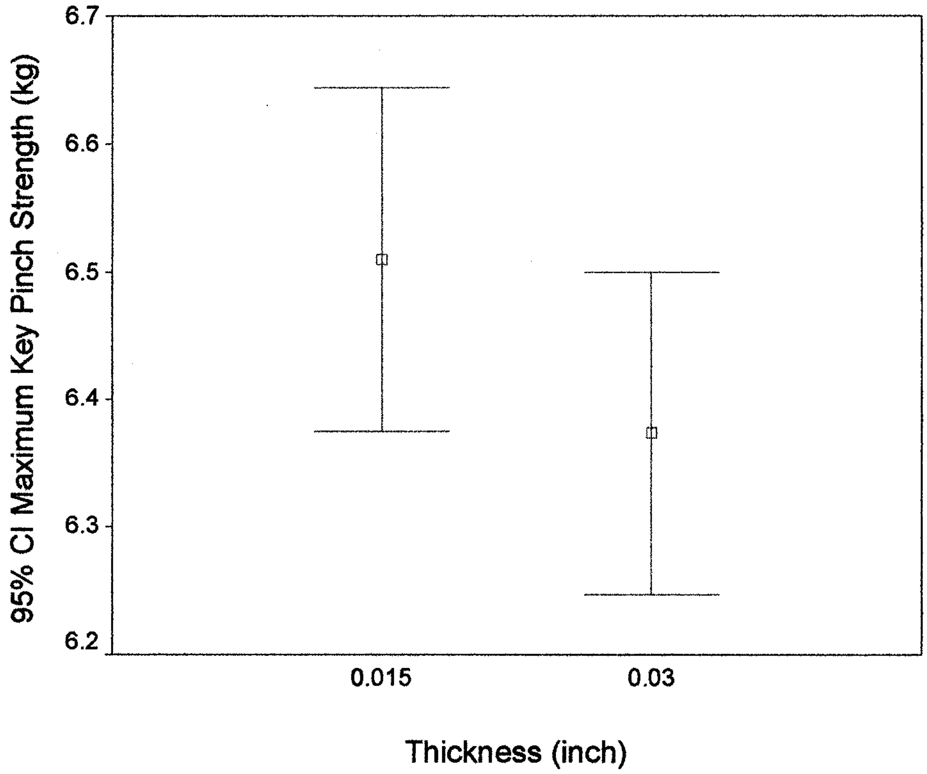


**Figure 24 Effect of thickness on maximum key pinch strength for eleven female subjects**

### 4.5 Effects on Contact Forces

Appendices 5-7 report the median, minimum, and maximum of the contact force values measured for roller, tweezers and wrench tasks. To evaluate the effects of glove and task demand, the contact forces measured at each of the four hand digits (tip of thumb, 2nd phalange of index finger, tip of middle and ring fingers) when performing roller tasks, at the tip of thumb and tip of index finger when performing tweezers tasks, and at each of the three hand digits (the tip of thumb, 2nd phalange of index finger, and 2nd phalange of middle finger) and palm region when performing wrench tasks were first

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

subjected to normality and equal error variance tests. The results of the Kolmogorov-Smirnov and Levene tests (Table 11) show that the contact forces data did not pass one or both of the tests at each of the contact areas. Using $\log_{10}$ transformation, the data did pass both of the tests at all of the contact areas except at the tip of thumb for tweezers tasks. Separate repeated-measures ANOVAs were used to evaluate the effects of glove and task demand on the contact forces using the $\log_{10}$ transformation data except at the tip of thumb for tweezers tasks. The Friedman test was used to evaluate the effects of glove and task demand separately on the contact forces at the tip of thumb for tweezers tasks since the square root transformation data still did not pass the Levene test ($F=16.708, p<0.0001$).

**Table 11 Summary results of Kolmogorov-Smirnov and Levene tests for evaluating the effects of glove and task demand on contact forces**

| Tools | Test | Thumb | IF | MF | RF | Palm |
|---|---|---|---|---|---|---|
| Roller | KS | 1.51* | 1.14 | 1.49* | 1.76* | --- |
| | Levene | 1.97* | 1.97* | 2.01* | 3.50* | --- |
| Tweezers | KS | 2.00* | 1.90* | --- | --- | --- |
| | Levene | 5.42* | 4.56* | --- | --- | --- |
| Wrench | KS | 2.32* | 2.09* | 1.56* | --- | 2.52* |
| | Levene | 3.99* | 1.86* | 2.93* | --- | 5.25* |
| | | **$\text{Log}_{10}$ (Th)** | **$\text{Log}_{10}$ (IF)** | **$\text{Log}_{10}$ (MF)** | **$\text{Log}_{10}$ (RF)** | **$\text{Log}_{10}$ (Palm)** |
| Roller | KS | 0.50 | 0.91 | 0.90 | 0.68 | --- |
| | Levene | 1.50 | 1.08 | 1.13 | 0.82 | --- |
| Tweezers | KS | 1.01 | 1.08 | --- | --- | --- |
| | Levene | 2.16* | 1.26 | --- | --- | --- |
| Wrench | KS | 0.60 | 0.89 | 0.89 | --- | 0.80 |
| | Levene | 1.32 | 0.60 | 1.05 | --- | 1.02 |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 12 summarizes the repeated-measures ANOVA results of glove and target task demand and their interactions on contact forces for all three hand tools except at the tip of thumb when performing tweezers tasks. The result shows that the effect of glove is statistically significant on contact force at the second phalange of index finger (F=3.01, $p<0.05$) and at the tip of ring finger (F=2.62, $p<0.05$) for roller tasks, at the tip of index finger (F=3.97, $p<0.01$) for tweezers tasks, and at the $2^{nd}$ phalange of the middle finger (F=2.48, $p<0.05$) for wrench tasks. The null hypotheses (1) for contact force on these hand regions are rejected. The task demand factor is found to be statistically significant at the tip of thumb for wrench tasks ($p<0.01$) and at all the remaining contact areas ($p<0.0001$). The interaction of glove and target task demand is found to be statistically significant on the contact forces at the tip of thumb (F=2.14, $p<0.05$) for wrench tasks.

**Table 12 Summary results of repeated-measures ANOVA for effects of glove, target task demand and their interactions on contact forces for all three hand tools**

| Tools | Source | df | $\text{Log}_{10}$(Th) F | $\text{Log}_{10}$ (IF) F | $\text{Log}_{10}$(MF) F | $\text{Log}_{10}$(RF) F | $\text{Log}_{10}$(Palm) F |
|---|---|---|---|---|---|---|---|
| **Roller** | **G** | 6 | 1.66 | 3.01* | 1.16 | 2.62 * | --- |
| | **TD** | 2 | 47.78*** | 34.52*** | 15.59*** | 28.27*** | --- |
| | **G * TD** | 12 | 1.11 | 0.91 | 0.66 | 1.47 | --- |
| **Tweezers** | **G** | 6 | --- | 3.97** | --- | --- | --- |
| | **TD** | 2 | --- | 118.56*** | --- | --- | --- |
| | **G * TD** | 12 | | 0.93 | --- | --- | --- |
| **Wrench** | **G** | 6 | 1.00 | 1.00 | 2.48* | --- | 1.43 |
| | **TD** | 2 | 6.79** | 98.47*** | 56.67*** | --- | 17.00*** |
| | **G * TD** | 12 | 2.14* | 1.19 | 1.02 | --- | 0.70 |

G: glove; TD: Task demand; F: F value
* Significant at level α = 0.05
** Significant at level α = 0.01
*** Significant at level α = 0.0001

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Bonferroni post hoc analyses were conducted to determine which pairs of means (in log10 scale) were statistically significant. For the glove factor, the comparisons (Table 13) indicated that there were statistically significant differences for N15 vs. bare hand at the 2nd phalange of index finger and bare hand vs. H15 at the tip of ring finger for roller tasks, for B30, H15, N15, and B15 vs. bare hand at the tip of index finger for tweezers tasks, and for N30 vs. bare hand at the 2nd phalange of middle finger for the wrench tasks. These indicate that N15 glove increased the contact forces significantly at the 2nd phalange of the index finger and H15 glove decreased the contact forces significantly at the tip of ring finger compared to bare hand for roller tasks. B15, H15, N15, and B30 gloves increased the contact forces significantly at the tip of index finger compared to bare hand for tweezers tasks. In addition, N30 glove increased the contact forces significantly at the 2nd phalange of the middle finger compared to bare hand for wrench tasks. For the task demand factor, all three levels differed significantly from one another except at the tip of thumb for wrench tasks where significant mean contact force differences of 0.279 ($p$<0.01) in $\log_{10}$ scale were only found to be between 9.04 N-m and 1.13 N-m.

For the contact forces at the tip of thumb for tweezers tasks, the Friedman test rejected the null hypothesis (1) for contact force and showed significant differences between glove ($\chi^2$=32.29, Asymptotic Significance<0.05) and task demand ($\chi^2$=148.08, Asymptotic Significance<0.05). Wilcoxon signed-rank tests were then used to further understand which pairs of glove material are significant different. The results indicated that the pairs of gloves having significant differences were (B15, Bare), (B30, Bare),

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(H15, Bare), (H30, Bare), (N15, Bare), (N30, Bare), and (N15, B15) where the contact forces in the first glove of the pair yielded significant higher (Asymptotic Significance<0.05) contact forces than that of the second glove.

**Table 13 Bonferroni post hoc tests for glove effect on contact forces for all three hand tools**

| Tools | Contact area | (I) Glove | (J) Glove | Mean Difference (I-J)* | Sig. |
|---|---|---|---|---|---|
| Roller | IF | N15 | Bare hand | 0.2 | 0.031 |
|  | RF | Bare hand | H15 | 0.2 | 0.017 |
| Tweezers | IF | B30 | Bare hand | 4.4 | 0.000 |
|  |  | H15 | Bare hand | 3.8 | 0.008 |
|  |  | N15 | Bare hand | 3.5 | 0.019 |
|  |  | B15 | Bare hand | 3.3 | 0.036 |
| Wrench | MF | N30 | Bare hand | 0.2 | 0.026 |

* Mean differences in $\log_{10}$(Newton)

To evaluate the effects of glove material, thickness, layer, and task demand, the contact forces measured at each of the four hand digits when performing roller tasks, at the tip of thumb and tip of index finger when performing tweezers tasks, and at each of the three digits and palm region when performing wrench tasks were first subjected to the Kolmogorov-Smirnov and Levene tests. The results (Table 14) indicated that all the original data did not pass both of the tests at all of the contact areas. Taking log10 transformation, the sample data at all four contact areas for wrench tasks passed both of the tests. Taking square root transformation, the sample data at the tip of thumb and 2nd phalange of index finger for roller tasks passed both of the tests. Separate repeated-measures ANOVAs were used to evaluate the effects of glove material, thickness, layer, and task demand on the transformed $\log_{10}$ or square root data which passed both the tests.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

For the remaining four contact areas (tip of middle and ring fingers for roller tasks and tip of thumb and index fingers for the tweezers tasks), nonparametric Wilcoxon signed-rank test was used for evaluating the effects of thickness and nonparametric Friedman test was used for evaluating the effects of glove material, layer, and task demand on the contact forces at those areas.

**Table 14 Summary results of Kolmogorov-Smirnov and Levene tests for evaluating the effects of glove, thickness, layer, and task demand on contact forces**

| **Tools** | **Test** | **Thumb** | **IF** | **MF** | **RF** | **Palm** |
|---|---|---|---|---|---|---|
| Roller | KS | 2.21* | 2.00* | 2.48* | 2.98* | --- |
| | Levene | 1.78* | 1.91* | 3.92* | 4.17* | --- |
| Tweezers | KS | 2.66* | 2.33* | --- | --- | --- |
| | Levene | 4.59* | 4.03* | --- | --- | --- |
| Wrench | KS | 3.07* | 2.87* | 2.46* | --- | 4.15* |
| | Levene | 3.39* | 2.13* | 2.86* | --- | 4.63* |
| | | **Log$_{10}$ (Th)** | **Log$_{10}$ (IF)** | **Log$_{10}$ (MF)** | **Log$_{10}$ (RF)** | **Log$_{10}$ (Palm)** |
| Roller | KS | 0.85 | 1.11 | 0.88 | 0.97 | --- |
| | Levene | 1.83* | 1.29* | 2.43* | 2.09* | --- |
| Tweezers | KS | 1.53* | 1.46* | --- | --- | --- |
| | Levene | 0.76 | 1.15 | --- | --- | --- |
| Wrench | KS | 0.86 | 0.92 | 1.09 | --- | 1.10 |
| | Levene | 0.61 | 0.94 | 1.08 | --- | 0.72 |
| | | **SQRT (Th)** | **SQRT (IF)** | **SQRT (MF)** | **SQRT (RF)** | **SQRT (Palm)** |
| Roller | KS | 0.93 | 0.99 | 1.67* | 1.28 | --- |
| | Levene | 0.83 | 1.04 | 0.97 | 1.89* | --- |
| Tweezers | KS | 1.94* | 1.78* | --- | --- | --- |
| | Levene | 1.92* | 2.31* | --- | --- | --- |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The repeated-measures ANOVA results (Table 15) show that the effect of glove material is statistically significant at the tip of thumb (F=6.48, $p<0.01$) for wrench tasks. The null hypothesis (2) for palmar contact force at the tip of thumb for wrench tasks is rejected. The layer factor is found to be statistically significant at the tip of thumb (F=7.40, $p<0.01$) and 2nd phalange of index finger (F=3.74, $p<0.05$) for roller tasks and at the tip of thumb (F=7.38, $p<0.01$) for wrench tasks. The null hypotheses (4) for palmar contact force on these hand regions are rejected. The task demand factor is found to be statistically significant at the tip of thumb for wrench tasks ($p<0.01$) and at all the remaining contact areas ($p<0.001$) underwent repeated-measures ANVOA analyses. The interactions of thickness and target task demand (F=4.13, $p<0.05$) and layer and target task demand (F=4.08, $p<0.01$) are found to be statistically significant on the contact forces at the 2nd phalange of index finger for wrench tasks. No statistically significant effects for thickness on contact forces were found. The null hypotheses (3) for palmar contact force on these hand regions are not rejected.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Table 15 Summary results of repeated-measures ANOVA for effects of glove material, thickness, layer, target task demand, and their interactions on contact forces for roller and wrench for ten female subjects.**

| | | | **SQRT (Thumb)** | **SQRT (IF)** | | |
|---|---|---|---|---|---|---|
| **Tools** | **Source** | **df** | **F** | **F** | | |
| **Roller** | **GM** | 2 | 1.075 | 0.003 | | |
| | **TH** | 1 | 0.341 | 1.085 | | |
| | **L** | 2 | 7.397** | 3.742* | | |
| | **TD** | 2 | 71.917*** | 66.699*** | | |
| | | | **$\log_{10}$(Thumb)** | **$\log_{10}$(IF)** | **$\log_{10}$(MF)** | **$\log_{10}$(Palm)** |
| **Tools** | **Source** | **df** | **F** | **F** | **F** | **F** |
| **Wrench** | **GM** | 2 | 6.478** | 1.394 | 0.939 | 0.137 |
| | **TH** | 1 | 3.90 | 0.048 | 0.107 | 0.554 |
| | **L** | 2 | 7.378** | 3.118 | 0.224 | 1.142 |
| | **TD** | 2 | 8.723** | 116.639*** | 67.619*** | 12.194*** |
| | **L * TD** | 4 | --- | 4.075** | --- | --- |

GM: glove material; TH: Thickness; L: Layer
TD: Task demand; F: F value
*: Significant at level $\alpha = 0.05$; **: Significant at level $\alpha = 0.01$; ***: Significant at level $\alpha = 0.001$

Bonferroni post hoc analyses were conducted with repeated-measures ANOVAs to determine which pairs of means (in log10 or square root scale) were statistically significant. For the glove material factor, the pairwise comparisons (Table 16) indicated that there were statistically significant differences for butyl vs. hypalon at the tip of thumb for the wrench tasks. Hypalon material can significantly reduced the contact forces compared to the butyl material at the tip of the thumb for wrench tasks. For the layer factor, statistically significant differences were found between double and triple layers at the tip of thumb and 2nd phalange of the index finger for the roller tasks and between single and triple and double and triple layers at the tip of thumb for wrench tasks. Triple layers decreased the contact forces significantly compared to double layers

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

at the tip of thumb and 2nd phalange of the index finger for the roller tasks and to single and double layers at the tip of thumb for wrench tasks. For the task demand factor, all three levels differ significantly from one another except at the tip of thumb for wrench tasks where no significant difference was found between 4.57 N-m and 1.13 N-m. Figure 25 shows the plot of Thickness * Task Demand interaction at the 2nd phalange of index finger for wrench tasks. For low task demand (1.13 N-m), thick glove seems to increase the contact force while the opposite effect is observed on high task demand. Figure 26 shows the plot of Layer * Task Demand interaction at the 2nd phalange of index finger for wrench tasks. For low task demand (1.13 N-m), the contact force seems to increase as the number of layer increased while the opposite effects are observed on medium and high task demand.

**Table 16 Bonferroni post hoc tests for glove material and layer effects on contact forces for roller and wrench tasks**

| **Tools** | **Contact area** | **(I) GM** | **(J) GM** | **Mean Difference (I-J)*** | **Sig.** |
|---|---|---|---|---|---|
| Wrench | Thumb | Butyl | Hypalon | 0.1 | 0.033 |
| **Tools** | **Contact area** | **(I) L** | **(J) L** | **Mean Difference (I-J)** | **Sig.** |
| Roller | Thumb | Double | Triple | 0.2 | 0 |
|  | IF | Double | Triple | 0.2 | 0.026 |
| Wrench | Thumb | Single | Triple | 0.1 | 0.038 |
|  |  | Double | Triple | 0.1 | 0.037 |

* Roller: in SQRT(Newton); Wrench: in $\log_{10}$(Newton)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

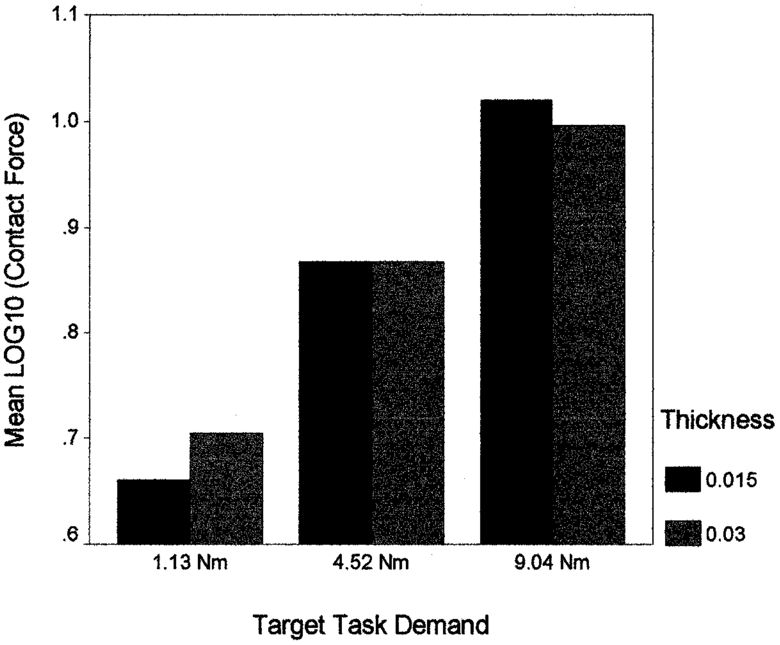


Figure 25 Interaction of Thickness * Task Demand on contact force at index finger when performing wrench tasks

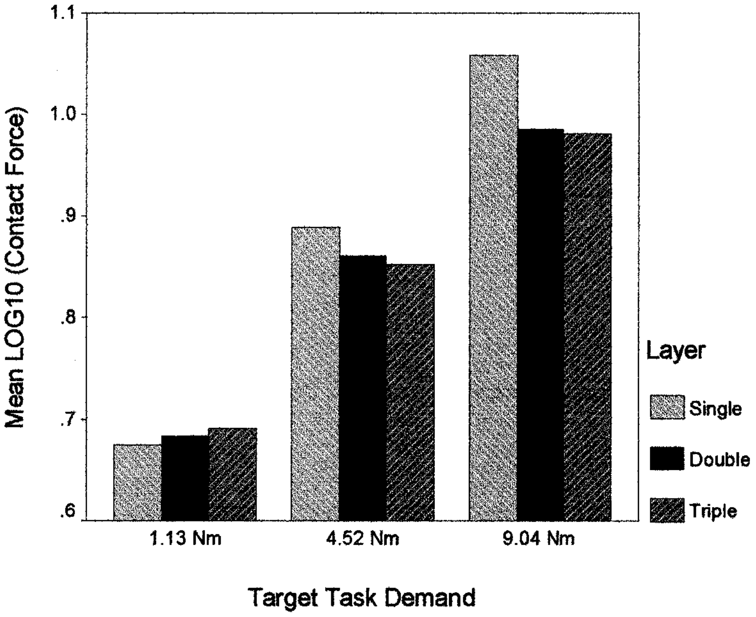


Figure 26 Interaction of Layer * Task Demand on contact force at index finger when performing wrench tasks

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The Friedman tests (Table 17) show significant differences on contact forces between glove material at the tip of middle and ring fingers for roller tasks and at the tip of thumb for tweezers tasks. Layer and task demand also show significant differences on contact forces at the tip of middle and ring fingers for roller tasks and at the tip of thumb and index finger for the tweezers tasks. The Wilcoxon signed-rank tests (Table 17) show significant differences on contact forces between thickness at the tip of middle and ring fingers for roller tasks and at the tip of thumb for tweezers tasks. Thinner gloves decreased the contact forces significantly compared to thicker gloves at the tip of middle (Figure 27) and ring (Figure 28) fingers for roller tasks and at the tip of thumb (Figure 29) for tweezers tasks.

**Table 17 Friedman and Wilcoxon signed-rank test results for effects of glove material, thickness, layer, and target task demand on contact forces for roller and tweezers tasks**

| **Tools** | **Factor** | **df** | **MF** | **RF** | **Test Statistics** |
|---|---|---|---|---|---|
| **Roller** | **GM** | 2 | 6.14* | 50.18*** | **Chi-Square** |
| | **TH** | 1 | -2.01* | -2.35* | **Z** |
| | **L** | 2 | 6.72* | 17.03*** | **Chi-Square** |
| | **TD** | 2 | 106.84*** | 189.91*** | **Chi-Square** |
| | | | **Thumb** | **IF** | |
| **Tweezers** | **GM** | 2 | 20.92*** | 3.04 | **Chi-Square** |
| | **TH** | 1 | -2.10* | -0.85 | **Z** |
| | **L** | 2 | 34.25*** | 10.46** | **Chi-Square** |
| | **TD** | 2 | 386.25*** | 358.92*** | **Chi-Square** |

GM glove material; TH Thickness; L Layer
TD Task demand;
* Significant at level α= 0.05
** Significant at level α= 0.01
*** Significant at level α= 0.001
Chi-Square Friedman test Z Wilcoxon Signed Ranks Test

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The Wilcoxon signed-rank tests were then performed to further understand which pairs of glove materials and layers were significantly different. The results indicated that the pairs of glove materials having significant differences were (Neoprene, Hypalon) at the tip of middle finger and (Neoprene, Hypalon), (Neoprene, Butyl), and (Butyl, Hypalon) at the tip of ring finger for roller tasks and (Butyl, Neoprene) at the tip of thumb for tweezers tasks where the contact forces in the first glove material of the pair yielded significant (Asymptotic Significance<0.05) higher contact forces than that of the second glove material. In addition, the pairs of layers having significant differences were (Double, Single) and (Double, Triple) at the tip of middle finger and (Double, Single) and (Triple, Single) at the tip of ring finger for roller tasks. For tweezers tasks, the pairs of layers having significant differences were (Single, Double), (Single, Triple) and (Double, Triple) at the tip of thumb and (Single, Triple) and (Double, Triple) at the tip of index finger. The contact forces in the first layer item of the pair yielded significant (Asymptotic Significance<0.05) higher contact forces than that of the second layer item.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

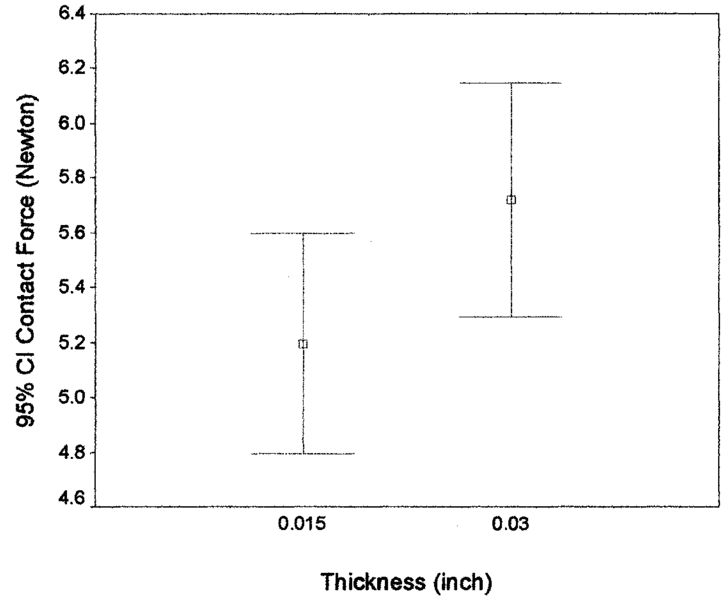


**Figure 27 Effect of thickness on contact forces at the tip of middle finger for roller tasks for ten female subjects**

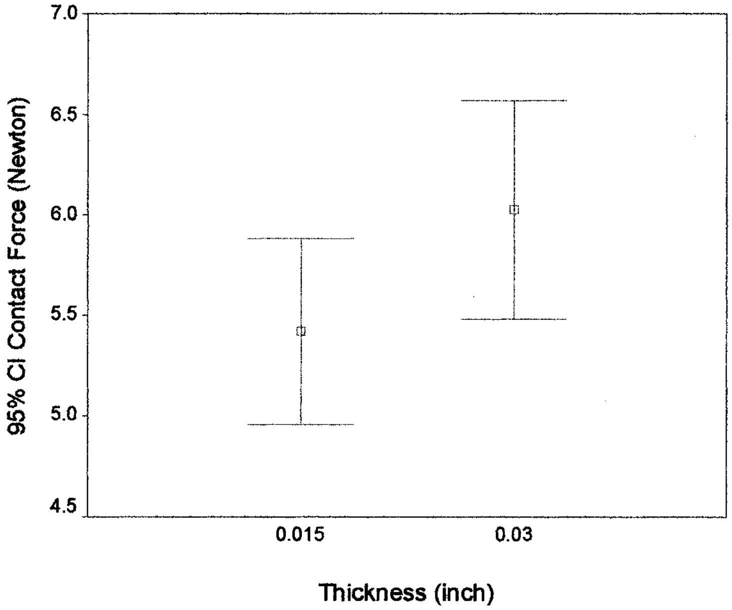


**Figure 28 Effect of thickness on contact forces at the tip of ring finger for roller tasks for ten female subjects**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

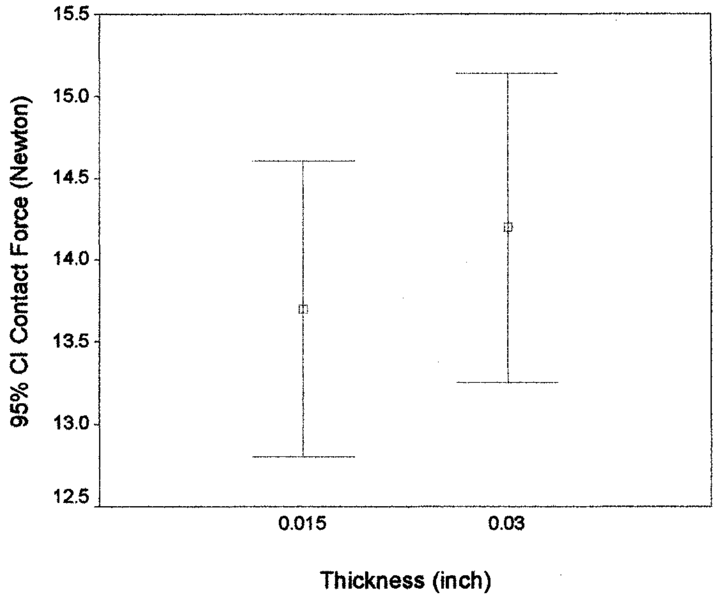


**Figure 29 Effect of thickness on contact forces at the tip of the thumb for tweezers tasks for eleven female subjects**

Paired-samples t testing (for correlated data) was used to compare the contact forces magnitudes estimated between thumb and index finger for tweezers tasks. The mean differences of bare and gloved hands were normally distributed tested by Kolmogorov-Smirnov test with greater than 0.05 Asymptotic Significances. The results shown in Table 18 indicate that the difference of force exertions between thumb and index finger is statistically significant ($t=3.19, p<0.01$) for the gloved hand. The contact forces estimated at the tip of thumb are 1.08 N higher than at the tip of index finger. For the bare hand, the contact forces estimated at the tip of thumb is also 1.33 N higher than at the tip of index finger but no statistically significant difference was found.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Table 18 Paired-samples t test for the contact forces between the thumb and index finger during tweezers task simulation for the eleven female subjects**

| | | Paired Differences | | 95% CI | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|
| | | **Mean*** | **SD** | **Lower** | **Upper** | | | |
| **Bare hand** | **Th-IF** | 1.3 | 8.1 | -1.55 | 4.20 | 0.94 | 32 | 0.3547 |
| **Gloved hand** | **Th-IF** | 1.0 | 8.3 | 0.41 | 1.74 | 3.19 | 593 | **0.0015** |

*: Mean in Newton

### 4.6 Effects of Properties of Glove Materials

Table 19 shows the determined values of coefficients of static friction and pliability for the glovebox gloves used in this study. A correlation analysis was performed on the independent and dependent variables. The independent variables were coefficients of static friction, pliability, thickness, and interaction, quadratic, and cubic relationships for the first three variables. The dependent variables were maximum grip strength, maximum key pinch strength, and contact forces divided by the task demands. The correlation matrix table (Table 20) indicates that the grip strength is the only dependent variable that significantly correlate ($p<0.05$) with most of the independent variables except friction, and quadratic and cubic components of friction variable. The results indicated the following conclusions.

(1) Thickness and pliability are inversely correlated to the maximum grip strength.

(2) No linear associations were found between coefficients of static friction and maximum grip strength.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(3) No linear associations are found between glove properties and maximum pinch strength.

(4) No linear associations are found between glove properties and contact forces.

Stepwise regression was preformed for automatically selecting significant variables to predict maximum grip strength. The result shows that the interaction of thickness and pliability ($t=-7.693$, $p<0.001$) is the only variable included in the equation and the final model is:

$$\text{Grip} = 24.6 - 145.6 * \text{Thickness} * \text{Pliability} \ (R^2 = 0.49, F=62.01, p<0.0001)$$

The low $R^2$ value of the equations may have been due to narrow range of thickness and pliability measured in this study. Batra et al. (1994) attributed their low $R^2$ value to the variations of glove-hand fit for the subjects, but, the method used to measure the glove-hand fit was not reported. The fitted regression model for the maximum grip strength is found to be significant ($F=59.18$, $p<0.0001$). The results indicate that the interaction of thickness and pliability is the best independent variable examined to predict the maximum grip strength measured in this study.

**Table 19 Static coefficients of friction and pliability of glovebox gloves**

| **Property/Glove** | **B15** | **B30** | **H15** | **H30** | **N15** | **N30** |
|---|---|---|---|---|---|---|
| **Friction** | 0.65 | 0.64 | 0.71 | 0.70 | 0.70 | 0.69 |
| **Pliability (kg)** | 0.42 | 0.71 | 0.53 | 0.88 | 0.42 | 0.98 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Table 20 Pearson correlations of glove properties with grip and key pinch strength and contact forces**

| | TH | Fric | Plia | TH*Plia | TH*Fric | Plia*Fric | Q_TH | Q_Fric | Q_Plia | C_TH | C_Fric | C_Plia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Grip** | ** | ns | ** | ** | ** | ** | ** | ns | ** | ** | ns | ** |
| **Pinch** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **RO_10N** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **RO_20N** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **RO_30N** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **TW_5N** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **TW_10N** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **TW_15N** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **WR_113** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **WR_452** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| **WR_904** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |

** Correlation is significant at the 0.01 level (2-tailed). ns: not statistically significant

TH: thickness; Fric: coefficients of static friction; Plia: pliability; TH*Plia: interaction of thickness and pliability; Q_TH: quadratic of thickness; C_TH: cubic of thickness;

RO, TW, WR: on all contact areas for roller, tweezers, and wrench tasks.

## 4.7 Effects on Tactility, Tingling, Comfort, and Preference

Appendix 8 reports the median, minimum, and maximum of the static two-point discrimination distance (mm) and the scores of subjective effects on tingling, comfort, and preference for different gloves of the eleven female subjects. The static two-point discrimination ranged from 2 to 4 mm and 2 to 5 mm for the bare and gloved hands, respectively.

To evaluate the effects of glove on these four dependent variables, two separate repeated-measured ANOVAs were conducted on tingling and comfort since the significances of both the KS and Levene tests of the original data were greater than 0.05 (Table 21). In addition, two separate Friedman tests were used on tactility and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

preference since both the original and transformed (log10 and square root) data did not pass at least one of the two tests.

**Table 21 Summary results of Kolmogorov-Smirnov and Levene tests on tactility, tingling, comfort, and preference for evaluating the glove effects**

| Test/variable | Tactility | Tingling | Comfort | Preference |
|---|---|---|---|---|
| KS | 2.60* | 0.75 | 0.53 | 1.16 |
| Levene | 2.57 * | 0.27 | 0.20 | 4.20 * |
|  | **Log10** |  |  | **Log10** |
| KS | 2.60* |  |  | 1.42* |
| Levene | 0.26 |  |  | 7.37* |
|  | **SQRT** |  |  | **SQRT** |
| KS | 2.40* |  |  | 1.27 |
| Levene | 0.05 |  |  | 5.39* |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

The repeated-measures ANOVAs indicated that there were significant differences between tingling (F=187.78, $p<0.001$) and comfort (F=295.48, $p<0.001$) in different gloves. The Bonferroni post hoc analyses (Table 22) show statistically significant differences between all pair comparisons of means except the pair comparisons between B15, H15, and N15 gloves for tingling and comfort and between H30 and N30 gloves for comfort. The results indicate that tingling sensation and discomfit scores for all gloved hands are significantly higher than that of bare hand. The Friedman tests showed statistically significant differences between tactility ($\chi^2=55.39$, Asymptotic Significance<0.001) and preference ($\chi^2=62.36$, Asymptotic Significance<0.001) in different gloves. The Bonferroni analyses (Table 23) show

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

statistically significant differences for N30 vs. Bare and H30 vs. Bare for the tactility and all gloves vs. bare hand for the preference. The results indicate that bare hand is most preferred among all glove conditions and N30 and H30 gloves decreased the tactile performance significantly compared to that of bare hand. In summary, the null hypotheses (1) for subjective hand performances have all been rejected.

To evaluate the effects of glove material and thickness on these four dependent variables, a repeated-measured ANOVAs were conducted on the preference since the significances of both the KS and Levene tests of the original data were greater than 0.05 (Table 24). In addition, separate Friedman tests were used to evaluate the effects of glove material and separate Wilcoxon signed-rank tests were used to evaluate the effect of thickness on tactility, tingling, and comfort since both the original and transformed (log10 and square root) data did not pass the normality tests.

**Table 22 Bonferroni post hoc tests for glove on tingling and comfort for eleven female subjects**

| | (I) Glove | (J) Glove | Mean Difference (I-J)* | t | Sig. |
|---|---|---|---|---|---|
| **Tingling** | B15 | Bare | 0.7 | 5.756 | <0.001 |
| | B30 | Bare | 1.8 | 15.35 | <0.001 |
| | H15 | Bare | 0.6 | 5.373 | <0.001 |
| | H30 | Bare | 2.5 | 21.49 | <0.001 |
| | N15 | Bare | 0.7 | 5.756 | <0.001 |
| | N30 | Bare | 3.1 | 26.095 | <0.001 |
| **Comfort** | B15 | Bare | 1.1 | 9.417 | <0.001 |
| | B30 | Bare | 2.7 | 23.15 | <0.001 |
| | H15 | Bare | 1.1 | 9.809 | <0.001 |
| | H30 | Bare | 0.7 | 6.278 | <0.001 |
| | N15 | Bare | 1.1 | 9.417 | <0.001 |
| | N30 | Bare | 3.8 | 32.567 | <0.001 |

* Borg 10 scale

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### Table 23 Bonferroni tests for glove on tactility and preference for eleven female subjects

| | (I) Glove | (J) Glove | Mean Difference (I-J)* | t | Sig. |
|---|---|---|---|---|---|
| **Tactility** | N30 | Bare | 1.0 | 11.328 | <0.001 |
| | H30 | Bare | 1.0 | 10.299 | <0.001 |
| **Preference** | N30 | Bare | 5.7 | 25.37 | <0.001 |
| | H30 | Bare | 5.2 | 22.954 | <0.001 |
| | B30 | Bare | 4.1 | 18.121 | <0.001 |
| | H15 | Bare | 2.7 | 12.081 | <0.001 |
| | N15 | Bare | 1.7 | 7.651 | <0.001 |
| | B15 | Bare | 1.5 | 6.846 | <0.001 |

* Tactility in mm

### Table 24 Summary results of Kolmogorov-Smirnov and Levene tests on tactility, tingling, comfort, and preference for evaluating the glove material and thickness effects for eleven female subjects

| Test/variable | Tactility | Tingling | Comfort | Preference |
|---|---|---|---|---|
| KS | 2.37* | 2.07* | 1.87* | 1.29 |
| Levene | 0.09 | 2.57* | 0.24 | 1.44 |
| | **Log10** | **Log10** | **Log10** | |
| KS | 2.32* | 1.94* | 1.62* | |
| Levene | 0.27 | 3.27 | 3.22 | |
| | **SQRT** | **SQRT** | **SQRT** | |
| KS | 2.19 * | 2.01 * | 1.76 * | |
| Levene | 0.06 | 1.93 | 1.20 | |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

The repeated-measures ANOVA indicated that there were significant differences between preference in different glove materials (F=28.38, $p$<0.001) and thicknesses

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(F=529.78, $p<0.001$). The null hypotheses (2) and (3) for preference are rejected. The subjects preferred thinner gloves (3) than the thicker glove (6) with the mean rank inside the parenthesis. The interaction of glove material and thickness is also found to be statistically significant (F=14.76, $p<0.01$). Bonferroni post hoc analyses for glove material factor showed that there were statistically significant differences for hypalon vs. butyl (F=5.18, $p<0.001$) and neoprene vs. butyl (F=4.14, $p<0.01$). The results indicate that the subjects' rank of most preferred to least preferred glove material with mean rank inside parenthesis are butyl (3.82) > Neoprene (4.73) = hypalon (4.96). Figure 30 shows the plot of Glove Material * Thickness interaction. For thin gloves, the most and least preferred glove material are butyl/neoprene and hypalon materials while the most and least preferred glove materials for thick gloves are butyl and neoprene materials, respectively.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

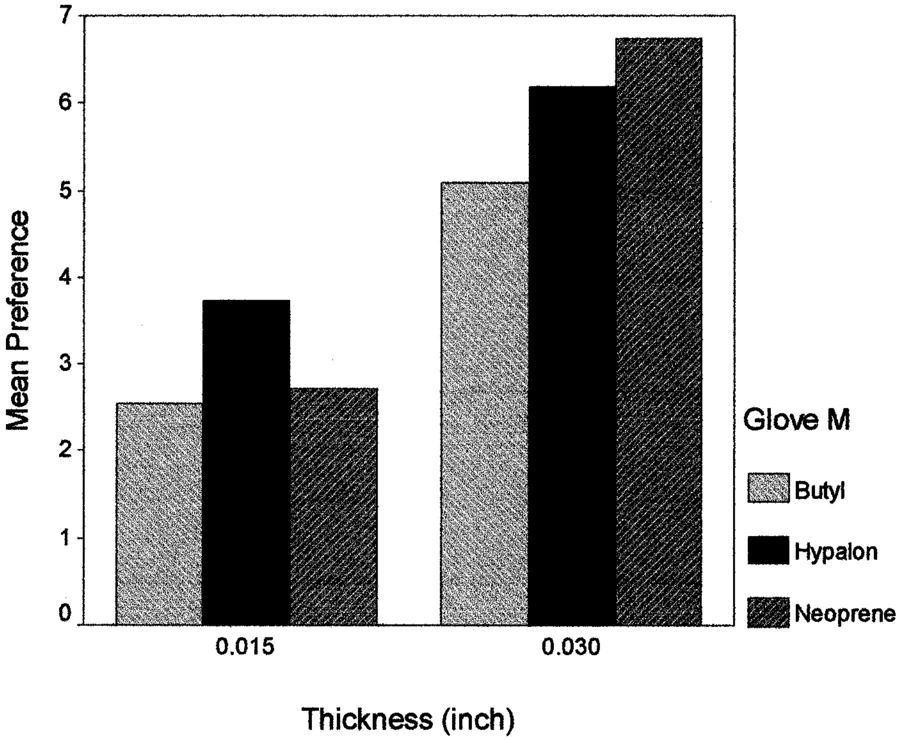


**Figure 30 Interaction of Glove Material * Thickness on preference for eleven female subjects**

The Friedman tests showed statistically significant differences between tactility ($\chi^2$=14.25, Asymptotic Significance<0.001), tingling ($\chi^2$=15.53, Asymptotic Significance<0.001), and comfort ($\chi^2$=15.53, Asymptotic Significance<0.001) in different glove materials. The Wilcoxon signed-rank tests were then performed to further understand which pairs of glove materials are significantly different. The results indicated that the pairs of glove materials having significant differences in tactility were (Hypalon (2.14), Butyl(1.66)) and (Neoprene (2.20), Butyl (1.66)), in tingling were (Hypalon (1.98), Butyl (1.55)), (Neoprene (2.48), Butyl (1.55)), and (Neoprene (2.48), Hypalon (1.98)), and in comfort were (Hypalon (2.14), Butyl (1.48)) and (Neoprene

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(2.39), Butyl (1.48)) with Asymptotic Significance<0.05 and mean rank inside parenthesis.

In addition, the Wilcoxon signed-rank tests indicated statistically significant differences between tactility (Z=-4.90, Asymptotic Significance<0.001), tingling (Z=-5.04, Asymptotic Significance<0.001), and comfort (Z=-5.05, Asymptotic Significance<0.001) in different thicknesses. The thinner gloves retain better (lower mean) tactility, tingling, and comfort performances than the thicker gloves.

In Summary, the null hypotheses (2) and (3) for tactility, tingling, and comfort have all been rejected.

### 4.7.1 Linear Relationship between Tactility and Pliability

Tsaousidis and Freivalds (1998) stated that higher glove pliability decreased tactile information of the hand. However, the effects of glove pliability on hand tactility have not been tested. A correlation analysis was performed between the tactility with pliability, and quadratic and cubic components of pliability. The Pearson correlation shows that the tactility and are positively correlated to pliability (Pearson correlation=0.546, $p<0.01$), quadratic of pliability (Pearson correlation=0.554, $p<0.01$), and cubic of pliability (Pearson correlation=0.555, $p<0.01$). Stepwise regression was preformed for automatically selecting significant pliability terms to predict tactility. The result shows that the cubic term of pliability (t=5.34, p<0.001) is the only variable included in the equation and the final model is:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Tactility = 2.696 + 1.273 * Cubic of Pliability ($R^2 = 0.31$, F=28.56, $p<0.0001$)

Pliability could increase the tactility spacing distance and decrease the tactile sensitivity.

### 4.8 Estimated Tendon and Muscle Forces

Appendix 9 shows an example for constructing force and moment equations using equations (4), (5), and (6). Applying Chao et al.'s (1989) 3D biomechanical model, the admissible solutions of tendon and muscle forces ranged from one for the thumb to six or seven for the fingers in the present study. Appendices 10-12 report the median, minimum, and maximum of the tendon and muscle forces estimated in the thumb and index, middle, and ring fingers for the roller tasks, in the thumb and index finger for the tweezers tasks, and in the thumb and index and middle fingers for the wrench tasks.

Tendon and muscle forces were found for the flexor pollicis longus (FPL), abductor pollicis brevis (APB), and adductor pollicis (ADD) of the thumb and for the terminal extensor (TE), flexor profundus (FP), radial band (RB), ulnar band (UB), radial interosseous (RI) of the fingers for all three tasks. In addition, lumbrical muscle (LU) forces were also found in the index finger for roller tasks and in the index and middle fingers for the wrench tasks. The abductor pollicis brevis, the major functional tendon of the thumb, had forces ranging from 6.7 to 6.84 times, 7.03 to 7.2 times, and 6.61 to 6.84 times the externally applied forces (contact forces) in the roller, tweezers, and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

wrench tasks, respectively. The terminal extensor and flexor profundus are the major functional tendons for the fingers included in the roller, tweezers, and wrench tasks simulations. For the roller tasks simulations, the forces estimated in the TE and FP of the index finger ranged from 1.96 to 2.27 times and 1.85 to 2.14 times the externally applied forces, respectively. The forces estimated in the TE and FP of the middle finger ranged from 7.27 to 7.69 times and 7.90 to 8.54 times the externally applied forces, respectively. The forces estimated in the TE and FP of the ring finger ranged from 6.97 to 8.08 times and 7.29 to 8.6 times the externally applied forces, respectively. For the tweezers tasks, the forces estimated in the TE and FP of the index finger ranged from 4.06 to 4.27 times and 4.86 to 9.79 times the externally applied forces, respectively. For the wrench tasks, the forces estimated in the TE and FP of the index finger ranged from 2.03 to 2.2 times and 1.91 to 2.07 times the externally applied forces, respectively. The forces estimated in the TE and FP of the middle finger ranged from 2.22 to 2.49 times and 2.0 to 2.21 times the externally applied forces, respectively.

### 4.8.1 Effects on Tendon and Muscle Forces

To evaluate the effects of glove and task demand, the tendons and muscle forces estimated for the four hand digits (thumb, index finger, middle, and ring fingers) for roller tasks, for the two hand digits (thumb and index finger) for tweezers tasks, and for the three hand digits (thumb, index finger, and middle finger) for wrench tasks were first subjected to normality and equal error variance tests. The results of the Kolmogorov-Smirnov and Levene tests (Appendix 13) show that the forces estimated in the following

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

tendons and muscles passed both tests and can be treated using repeated-measures ANOVAs. For roller tasks, the log10 transformed tendon and muscle forces in FPL, APB, and ADD of the thumb, in TE, FP, RB, UB, RI, and LU of the index finger, in TE, FP, RB, UB, and RI of the middle finger and in TE, FP, RB, and UB of the ringer fingers and the square root transformed tendon and muscle forces in RI of the ring finger. For tweezers tasks, the log10 transformed tendon and muscle forces in APB of the thumb and in FP and RI of the index finger. For wrench tasks, the log10 transformed tendon and muscle forces in FPL, APB, and ADD of the thumb and in TE, FP, RB, UB, RI, and LU of the index and middle fingers. For those did not pass at least one of the two tests, the Friedman test was used to evaluate the effects of glove and task demand separately on the tendon and muscle forces in FPL and ADD of the thumb and in TE, RB, and UB of the index finger for tweezers tasks.

Table 25 summarizes the repeated-measures ANOVA results of effect of glove on the tendon and muscle forces. For roller tasks, the effect of glove is statistically significant on the tendon and muscle forces in TE, FP, RB, UB, RI, and LU of the index finger and in TE, FP, RB, UB, and RI of the ring finger. For tweezers tasks, the effect of glove is statistically significant on the tendon and muscle forces in APB of the thumb and in FP and RI of the index finger. For wrench tasks, the effect of glove is statistically significant on the tendon and muscle forces in TE, FP, RB, UB, and LI of the middle finger. The null hypotheses (1) for tendons and muscle forces on these tendons and muscles are rejected. The task demand factor is found to be statistically significant at $p$<0.001 on the forces in all the tendons and muscles treated with repeated-measures

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ANOVAs except in FPL, APB, and ADD of the thumb for wrench tasks where they are statistically significant at $p<0.01$. The interaction of glove and task demand is found to be statistically significant on the tendon and muscle forces in TE (F=1.89, $p<0.05$), FP (F=1.96, $p<0.05$), RB (F=1.90, $p<0.05$), UB (F=1.94, $p<0.05$), and RI (F=2.64, $p<0.05$) of the ring finger for roller tasks and in FPL (F=2.15, $p<0.05$), APB (F=2.14, $p<0.05$), and ADD (F=2.14, $p<0.05$) of the thumb for wrench tasks.

**Table 25 Summary of repeated-measures ANOVA results for effects of glove on tendon and muscle forces for three tools for eleven (tweezers) or ten (roller and wrench) female subjects**

| Digit | Tools | Muscles/Tendons | | | | | |
|---|---|---|---|---|---|---|---|
| **Thumb** | | **FPL** | **APB** | **ADD** | | | |
| | Roller | 1.99 | 1.80 | 1.85 | | | |
| | Tweezers | --- | 3.52** | --- | | | |
| | Wrench | 1.00 | 1.00 | 1.00 | | | |
| **IF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 4.13** | 4.09** | 4.49** | 2.65* | 2.45* | 6.72** |
| | Tweezers | --- | 4.40** | --- | --- | 4.36* | --- |
| | Wrench | 0.90 | 0.90 | 0.87 | 0.98 | 1.21 | 1.00 |
| **MF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 1.45 | 1.40 | 1.43 | 1.44 | 0.81 | --- |
| | Wrench | 2.43* | 2.43* | 2.50* | 2.30* | 2.25 | 3.43** |
| **RF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 2.55* | 2.54* | 2.55* | 2.52* | 3.64** | --- |

| | |
|---|---|
| * | $p < 0.05$ |
| ** | $p < 0.01$ |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Bonferroni post hoc analyses were conducted to determine which pairs of means (in log10 or square root scale) were statistically significant. For the glove factor, the comparisons (Table 26) indicated that various gloves increased the forces significantly compared to bare hand in TE, FP, RB, UB, RI, and LU of the index finger for the roller tasks, and in APB of the thumb and in FP and RI of the index finger for the tweezers tasks. Neoprene gloves in 0.03" thickness also increased the forces significantly in TE, FP, RB, UB, RI, and LU of the middle finger for the wrench tasks. On the contrary, H15 glove decreased the forces significantly compared to bare hand in TE, FP, RB, and UB of the ring finger for the roller tasks. B30, H15, H30, N15, and H30 gloves also decreased the forces significantly compared to bare hand in RI of the ring finger for the roller tasks. For the task demand factor, all three levels differ significantly from one another in all the tendons and muscles treated with repeated-measures ANOVAs except in the FPL ($t=5.14, p<0.05$), APB ($t=5.14, p<0.05$), and ADD ($t=5.14, p<0.05$) of the thumb for wrench tasks where significant mean differences in log10 scale were only found to be between 9.04 N-m and 1.13 N-m.

For the forces in FPL and ADD of the thumb and in TE, RB, and UB of the index finger for tweezers tasks, the Friedman tests showed significant differences between gloves in TE ($\chi^2=36.31$, Asymptotic Significance<0.05), RB ($\chi^2=37.70$, Asymptotic Significance<0.05), and UB ($\chi^2=34.32$, Asymptotic Significance<0.05) of the index finger for tweezers tasks where the most and least tendon and muscle forces were estimated for N30 glove and bare hand. The Friedman tests also showed significant differences between task demand in FPL ($\chi^2=22$, Asymptotic Significance<0.05) and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ADD ($\chi^2$=22, Asymptotic Significance<0.05) of the thumb, and in TE ($\chi^2$=22, Asymptotic Significance<0.05), RB ($\chi^2$=22, Asymptotic Significance<0.05), and UB ($\chi^2$=22, Asymptotic Significance<0.05) of the index finger for tweezers tasks.

**Table 26 Bonferroni post hoc tests for pairs of gloves with significant differences for tendons and muscles treated with repeated-measures ANOVA**

| Tools | Digit | Tendons | The Pairs with Significant Differences* |
|---|---|---|---|
| Roller | IF | TE, FP | (N15, Bare); (B30, Bare); (H15, Bare); (H30, Bare); (N30, Bare) |
| | | RB | (H30, Bare); (N15, Bare); (H15, Bare); (N30, Bare) |
| | | UB | (N15, Bare); (H15, Bare) |
| | | RI | (N15, Bare) |
| | | LU | (B30, Bare); (H30, Bare); (N30, Bare); (B15, Bare); (H15, Bare); (N15, Bare) |
| | RF | TE, FP, RB, UB | (Bare, H15) |
| | | RI | (Bare, H30); (Bare, N30); (Bare, H15); (Bare, B30); (Bare, N15) |
| Tweezers | TH | APB | (B15, Bare); (H30, Bare); (N30, Bare); (B30, Bare) |
| | IF | FP, RI | (B30, Bare); (H15, Bare); (N15, Bare); (B15, Bare); (N30, Bare); (H30, Bare) |
| Wrench | MF | TE, FP, RB, UB, RI, LU | (N30, Bare) |

* Significant at $p<0.5$. The tendon and muscle force in the first glove is greater than the second glove.

To evaluate the effects of glove material, thickness, layer, and task demand, the tendons and muscle forces estimated for the four hand digits for roller tasks, for the two hand digits for tweezers tasks, and for the three hand digits (thumb, index finger, and middle finger) for wrench tasks were first subjected to normality and equal error variance tests. The results of the Kolmogorov-Smirnov and Levene tests (Appendix 13)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

show that the forces estimated in the following tendons and muscles passed both tests and can be treated using repeated-measures ANOVAs. For roller tasks, the log10 transformed tendon and muscle forces in FPL and ADD of the thumb, in TE, FP, RB, RI, and LU of the index finger, in TE, FP, RB, UB, and RI of the middle finger and in TE, FP, RB, and UB of the ringer fingers. The square root transformed tendon and muscle forces in APB of the thumb, UB of the index finger, and RI of the ring finger. For tweezers tasks, the log10 transformed tendon and muscle forces in APB of the thumb. For wrench tasks, the log10 transformed tendon and muscle forces in FPL, APB, and ADD of the thumb and in TE, FP, RB, UB, RI, and LU of the index and middle fingers. For those did not pass at least one of the two tests, the Friedman test was used to evaluate the effects of glove material, layer, and task demand separately on the tendon and muscle forces in APB and ADD of the thumb and in TE, FP, RB, UB, and RI of the index finger for tweezers tasks.

Tables 27, 28 and 29 summarize the repeated-measures ANOVA results for the effects of glove material, thickness, and layer on the tendons and muscles forces. The results show that the effect of glove material factor is statistically significant for the forces in FPL, APB, and ADD of the thumb for wrench tasks. The null hypotheses (2) for tendons and muscle forces on these tendons and muscles are rejected. The layer factor is statistically significant for the forces in FPL, APB, and ADD of the thumb and in TE, FP, RB, RI, and LU of index finger for the roller tasks. The layer factor is also statistically significant for the forces in FPL of the thumb for tweezers tasks and in FPL, APB, and ADD of the thumb for wrench tasks. The null hypotheses (4) for tendons and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

muscle forces on these tendons and muscles are rejected. The task demand factor is statistically significant at $p<0.01$ for the forces in FPL, APB, and ADD of the thumb for the wrench tasks and at $p<0.0001$ for the forces in the remaining tendons and muscles treated with repeated-measures ANOVAs. The interaction of glove and thickness is statistically significant for the forces in TE (F=4.33, $p<0.05$), FP (F=4.25, $p<0.05$), RB (F=4.35, $p<0.05$), and UB (F=4.37, $p<0.05$) of the middle finger for roller tasks. The interaction of layer and task demand is statistically significant for the forces in TE (F=4.14, $p<0.05$), FP (F=4.10, $p<0.05$), RB (F=4.06, $p<0.05$), UB (F=4.25, $p<0.05$), RI (F=4.24, $p<0.05$), and LU (F=4.11, $p<0.05$) of the index finger for the wrench tasks. No statistically significant effects for thickness for forces in tendon and muscles were found.

**Table 27 Summary of repeated-measures ANOVA results for effects of glove material on tendon and muscle forces for three tools for eleven (tweezers) or ten (roller and wrench) female subjects**

| Digit | Tools | Muscles/Tendons | | | | | |
|---|---|---|---|---|---|---|---|
| **Thumb** | | **FPL** | **APB** | **ADD** | | | |
| | Roller | 1.11 | 1.09 | 1.09 | | | |
| | Tweezers | 2.90 | --- | --- | | | |
| | Wrench | 6.50** | 6.39** | 6.47** | | | |
| **IF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 0.01 | 0.01 | 0.08 | 0.22 | 0.28 | 0.06 |
| | Wrench | 1.28 | 1.26 | 1.22 | 1.41 | 1.51 | 1.91 |
| **MF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 1.16 | 1.18 | 1.16 | 1.14 | 0.92 | --- |
| | Wrench | 0.88 | 0.86 | 0.84 | 0.93 | 1.06 | 0.90 |
| **RF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 3.35 | 3.35 | 3.33 | 3.35 | 0.18 | --- |

** $p < 0.01$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 28 Summary of repeated-measures ANOVA results for effects of thickness on tendon and muscle forces for three tools for eleven (tweezers) or ten (roller and wrench) female subjects

| Digit | Tools | Muscles/Tendons | | | | | |
|---|---|---|---|---|---|---|---|
| **Thumb** | | **FPL** | **APB** | **ADD** | | | |
| | Roller | 0.83 | 0.34 | 0.84 | | | |
| | Tweezers | 1.27 | --- | --- | | | |
| | Wrench | 3.93 | 3.89 | 3.91 | | | |
| **IF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 0.93 | 0.98 | 0.01 | 3.70 | 4.71 | 0.18 |
| | Wrench | 0.12 | 0.12 | 0.19 | 0.05 | 0.24 | 0.21 |
| **MF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 1.91 | 1.69 | 1.91 | 1.85 | 0.95 | --- |
| | Wrench | 0.15 | 0.15 | 0.16 | 0.10 | 0.11 | 0.68 |
| **RF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 0.98 | 1.00 | 1.03 | 1.03 | 4.36 | --- |

Table 29 Summary of repeated-measures ANOVA results for effects of layer on tendon and muscle forces for three tools for eleven (tweezers) or ten (roller and wrench) female subjects

| Digit | Tools | Muscles/Tendons | | | | | |
|---|---|---|---|---|---|---|---|
| **Thumb** | | **FPL** | **APB** | **ADD** | | | |
| | Roller | 9.53** | 7.47** | 9.52** | | | |
| | Tweezers | 11.66** | --- | --- | | | |
| | Wrench | 7.34** | 7.45** | 7.40** | | | |
| **IF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 4.60* | 4.48* | 4.42* | 3.08 | 4.49* | 4.47* |
| | Wrench | 3.02 | 3.08 | 3.04 | 2.94 | 3.09 | 3.08 |
| **MF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 1.60 | 1.61 | 1.55 | 1.60 | 1.53 | --- |
| | Wrench | 0.22 | 0.22 | 0.23 | 0.21 | 0.23 | 0.21 |
| **RF** | | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| | Roller | 2.97 | 2.89 | 2.90 | 2.88 | 3.40 | --- |

* $p < 0.05$
** $p < 0.01$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Bonferroni post hoc analyses (Table 30) were conducted to determine which pairs of means (in log10 or square root scale) were statistically significant. For the glove material factor, the comparisons indicated that neoprene material increased the forces significantly compared to hypalon material in TE, FP, RB, and UB of the ring finger for roller tasks. In addition, butyl material increased the forces significantly compared to hypalon material in FPL, APB and ADD of the thumb for wrench tasks. For the layer factor, double layers increased the forces significantly compared to triple layers material in FPL, APB and ADD of the thumb, in TE, FP, RB, UB, RI, and LU of the index finger, and in RI of ring finger for roller tasks. As single layer increased the forces significantly compared to double and triple layers in FPL of the thumb for tweezers tasks. In addition, single and double layers increased the forces significantly compared to triple layers in FPL, APB, and ADD of the thumb for wrench tasks. For the task demand factor, all three levels differed significantly from one another in all the tendons and muscles treated with repeated-measures ANOVAs except in the FPL, APB, and of the thumb for wrench tasks where significant mean differences in log10 scale were only found to be between 9.04 N-m and 1.13 N-m.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### Table 30 Bonferroni post hoc tests for pairs of glove materials and layers with significant differences for tendons and muscles treated with repeated-measures ANOVA

| | Tools | Digit | Tendons | The Pairs with Significant Differences* |
|---|---|---|---|---|
| **GM** | Roller | RF | TE, FP, RB, UB | (Neoprene, Hypalon) |
| | Wrench | TH | FPL, APB, ADD | (Butyl, Hypalon) |
| **Layer** | Roller | Thumb | FPL, APB, ADD | (Double, Triple) |
| | | IF | TE, FP, RB, UB, RI, LU | (Double, Triple) |
| | | RF | RI | (Double, Triple) |
| | Tweezers | Thumb | FPL | (Single, Double), (Single, Triple) |
| | Wrench | Thumb | FPL, APB, ADD | (Single, Triple), (Double, Triple) |

* Significant at $p<0.5$. The tendon and muscle force in the first item is greater than the second item.
GM glove material

For the forces in APB and ADD of the thumb and in TE, FP, RB, UB, and RI of the index finger for tweezers tasks, the Friedman tests (Table 31) show significant differences between glove materials, layers, and task demands in APB and ADD of the thumb and in TE, FP, RB, UB, and RI of the index finger for tweezers tasks. The Wilcoxon Signed Ranks Test (Table 31) show significant differences between thickness in APB and ADD of the thumb. The results indicate that the thinner gloves decreased the forces in APB (Figure 31) and ADD (Figure 32) of the thumb for tweezers tasks. The Wilcoxon signed-rank tests were then performed to further understand which pairs of glove materials and layers are significant different. The results indicated that the pairs of glove materials having significant differences were hypalon vs. butyl in the APB (Z=-3.38, Asymptotic Significance<0.05) and ADD (Z=-3.32, Asymptotic Significance

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

<0.05) of the thumb for tweezers tasks where the butyl material yielded significant higher forces than the hypalon material in APB and ADD.

**Table 31 Friedman and Wilcoxon tests the forces in APB and ADD of the thumb and in TE, FP, RB, UB, and RI of the index finger for tweezers tasks for eleven female subjects**

| | | | Friedman | | Wilcoxon |
|---|---|---|---|---|---|
| **Digits** | **Tendons** | **Glove Material** | **Layer** | **Task Demand** | **Thickness** |
| **Thumb** | **APB** | 23.39*** | 34.25*** | 386.25*** | -2.16* |
| | **ADD** | 23.39*** | 34.25*** | 386.25*** | -2.12* |
| **IF** | **TE** | 14.75*** | 10.46** | 358.92*** | -1.40 |
| | **FP** | 14.08*** | 10.46** | 358.92*** | -1.32 |
| | **RB** | 13.59** | 13.59** | 358.92*** | -1.69 |
| | **UB** | 14.78*** | 14.78** | 358.92*** | -0.73 |
| | **RI** | 15.42*** | 15.42** | 358.92*** | -1.01 |

| | |
|---|---|
| Friedman | Chi-Square |
| Wilcoxon Signed Ranks Test | Z value |
| * | Asymptotic Significance<0.05 |
| ** | Asymptotic Significance<0.01 |
| *** | Asymptotic Significance<0.001 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

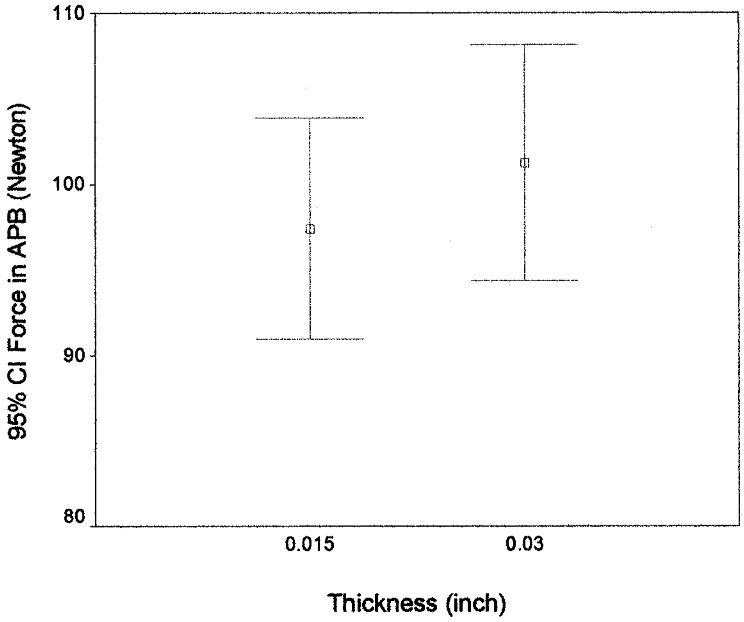


Figure 31 Effects of thickness on forces in APB of the thumb for tweezers tasks for eleven female subjects

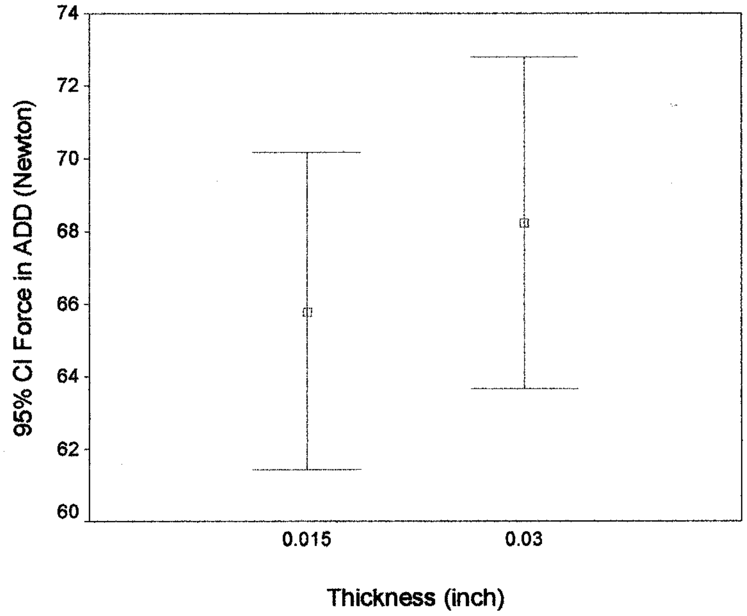


Figure 32 Effects of thickness on forces in ADD of the thumb for tweezers tasks for eleven female subjects

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# Chapter 5

# Discussion

The main objectives of this study were (1) to evaluate the commercially available glovebox gloves through performance tests and laboratory task simulations, and (2) to recommend ergonomics design/selection guidelines to prevent musculoskeletal disorders by minimizing effects on hand performance and optimizing protection of the hand. In this chapter, the ergonomics selection and design guidelines are recommended based upon the results of performance tests and task simulations.

## 5.1 Use of Anthropometry Data

Hand anthropometry is useful for determining various aspects of machines and hand tools (Imrhan et al. 1993). The anthropometry data are also widely used to eliminate or to minimize mismatch between workers and their working environment (Vasu and Mital, 2000). Glove design must also include prehension of the hand since hand anthropometry affects glove use and good design (Riley and Cochran 1988). Therefore, the hand anthropometric data should be accommodated and collected on a representative population in the design process of the glovebox gloves. Currently, no hand anthropometric data are available from the glovebox industries. Future studies are required to evaluate the anthropometric variations of the identified user group and accommodate those hand anthropometry data as one of the design criterion for glovebox gloves.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## 5.2 Guidelines Based on Grip Strength Results

The means and standard deviations of the maximum grip strength of the bare hand measured in this study are consistent with the normative data for female adults ranging from 20 to 44 years old reported by Mathiowetz et al (1985). The major finding is that all gloved hand situations impaired maximum grip strength significantly compared to the bare hand (Table 7) where the percentage of decrement ranging from 8.8% to 37.5% (Table 6). The results observed on the maximum grip strength are as expected and consistent based upon a review of the published literature of industrial gloves as shown in Chapter 2.2. The possible reasons for the reduction are reduction in inter-digit distances and reduction in range in motion (Buhman, et al. 2000), earlier pressing of the fingers with each other (Bishu and Klute 1995), interference of the glove in closing the hand around objects and the interference of the glove in tactile feedback (Cochran et al. 1986 and Batra et al. 1994), reduction in inter-digital pressure (Batra et al. 1994), and interference with digital flexion (Hallbeck and McMullin 1993).

For the effects of glove material, layer, and thickness on maximum grip strength, the findings of the present investigation are:

(1) Glove material affects the maximum grip strength where the butyl and hypalon gloves facilitated the highest grip strength values and the neoprene gloves recorded the lowest.

(2) The number of layers affects the maximum grip strength because the single gloving allowed the highest grip strength values followed by double and triple gloving conditions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(3) Thickness affects the maximum grip strength as the thinner (0.015") gloves performed better than thicker (0.03") gloves.

This is the first study to report that 1) butyl and hypalon gloves perform significantly better than neoprene gloves for maximum grip strength and 2) triple gloving reduces the maximum grip strength significantly compared to double gloving. The remaining findings are consistent with published literature and they are 1) double gloving degrades grip strength (Muralidhar et al. 1999) compared to the bare hand and 2) the thicker the gloves, the larger the reduction in maximum grip strength (Wang, 1991).

A limited pilot study was also performed to test the effects of glove material, thickness, and number of layers on the grip strength of three male subjects. The results of three male subjects indicated that there are significant differences in grip strength between glove material (F=22.2, $p<0.01$), thickness (F=26.0, $p<0.05$) and layer condition (F=14.1, $p<0.05$). Bonferroni pairwise comparisons in glove material effect show that there were statistically significant differences for butyl vs. neoprene (mean difference = 3.7 kg, $p<0.05$) indicating that the butyl gloves retain significantly higher maximum grip strength than the neoprene gloves. In layer effect, statistically significant differences were found for single vs. double (mean difference = 3.9 kg, $p<0.05$), single vs. triple (mean difference = 7.1 kg, $p<0.0001$), and double vs. triple (mean difference = 3.7 kg, $p<0.05$). The results indicate that more the layers of gloves are worn, the greater the grip strength reduction. The thin gloves retain significantly higher maximum grip strength (mean difference = 2.8 kg, $p<0.05$) than the thick gloves. The effects were

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

similar to that of female subjects. In addition, the male retain significantly higher grip strength (mean difference = 17.8 kg, $p<0.05$) than that of female.

To minimize effects of glovebox gloves on maximum grip strength based upon the observations made in this experiment, thinner gloves and single gloving condition should be used as selection and design considerations for glovebox gloves. In addition, butyl and hypalon gloves should be picked over neoprene gloves to minimize the reduction of grip strength if other criteria (chemical, physical, biological etc) were met.

### 5.3 Guidelines Based on Key Pinch Strength Results

The means and standard deviations of the maximum key pinch strength of the bare hand measured in this study are consistent with the normative data for female adults ranging from 20 to 44 years old reported by Mathiowetz et al (1985). The results of this study show that wearing glovebox gloves did not affect key pinch performance compared to bare hand. In addition, glove material and the number of layers of gloves included in this study did not affect the subjects' maximum key pinch strength capabilities. Thickness affects the maximum key pinch strength as the thinner (0.015") gloves performed better than thicker (0.03") gloves. The lack of effects of gloves on maximum pinch strength could be due to the absence of glove creases in the fingertip (Tsaousidis and Freivalds 1998) and to the extra cushioning provided at the point of contact (Muralidhar and Bishu 1994; Bishu and Klute 1995).

To minimize effects of glovebox gloves on maximum pinch strength, thinner gloves should be used as selection and design considerations for glovebox gloves.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 5.4 Guidelines Based on Contact Forces Results

When performing roller tasks, the thumb and index finger worked as a functional group to exert the desired task demand force and the middle and ringer fingers worked as the other functional group to support the roller tool and facilitate the roller tasks. When performing tweezers tasks, the thumb and index finger worked as a functional group to exert the desired task demand force. When performing wrench tasks, the index and middle fingers and H9 palm region worked as a functional group to exert the desired task demand torque and the function of the thumb included both the exerting and supporting purposes to facilitate the wrench tasks. The original assumption of this experiment was that glovebox gloves usage would dissipate the energy and reduce the contact forces (compared to the care hand) on the palmar skin of the hand. A hypalon glove of 0.015" thickness did meet the expectation to protect the ring finger (supporting group) from high mechanical stress (Table 13) for roller tasks. On the contrary, a neoprene glove of 0.015" thickness put more stress at the 2nd phalange of the index finger (exerting group) for roller tasks and a neoprene glove of 0.03" thickness put more stress at the 2nd phalange of the middle finger (exerting group) for wrench tasks. In addition, all six gloves except 0.03" butyl gloves increased the stress at the tip of thumb (exerting group) and butyl glove in 0.03" thickness and all 0.015" gloves put more stress at the tip of index finger (exerting group) for tweezers tasks. Glovebox gloves usage could reduce the contact forces for the supporting group of digits but could at the same time increase the contact forces for the exerting group of digits. The contact forces increment when glovebox gloves are donned could be attributed to the effects of gloves on the hand (ex.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

tactile perception) and glove material characteristics (ex. friction between hand and inner glove and friction between glove and tweezers).

For the effects of glove material, layer, and thickness on contact forces, the findings of the present investigation are:

(1) Hypalon material reduced the contact forces significantly compared to the neoprene material at the tip of middle finger and to both the butyl and neoprene materials at the tip of ring finger for roller tasks. In addition, hypalon material reduced the contact forces significantly compared to the butyl material at the tip of the thumb for wrench tasks.

(2) For roller tasks, triple layers decreased the contact forces significantly compared to double layers at the tip of thumb and 2nd phalange of the index finger. Single and triple layers decreased the contact forces significantly compared to double layers at the tip of middle ginger. In addition, single layer decreased the contact forces significantly compared to double and triple layers at the tip of ring finger. For tweezers tasks, triple layers decreased the contact forces significantly compared to single and double layers at the tip of thumb and index finger. For wrench tasks, triple layers decreased the contact forces significantly to single layer at the tip of thumb.

(3) Thinner gloves (0.015") decreased the contact forces significantly compared to thicker gloves (0.03") at the tip of middle and ring fingers for roller tasks and at the tip of thumb for tweezers tasks.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Triple layers show protection effects (lower contact forces) at most of the contact areas except at the tip of ring finger for roller tasks. The possible reason for the effects may be due to the increased total thickness for triple gloving condition. The air space between gloves may also provide some cushion effect and could reduce the contact forces for the triple gloving condition. In addition, the cotton glove used as the innermost glove for perspiration absorption may help reducing the total contact forces for roller tasks performed inside the glovebox. Muralidhar et al. (1999) stated that the thickness of the material employed in the glove is directly related to protection from potential hazards to the bare hands. However, thicker glove could increase the contact force magnitudes on the palmar skin of the hand.

To minimize the mechanical stress (optimize protection) on palmar skin of the hand, hypalon material could be selected if other criteria (such as chemical, physical, biological etc) were met since it could offer protection for specific hand regions (tip of thumb and tip of middle and ring fingers) with the lowest contact forces recorded. Thinner gloves could be used to reduce the contact force at the tip of thumb and tip of middle and ring fingers. In addition, triple gloving could be used to lower the contact forces at the tip of thumb, at the tip of index and middle fingers, and at the 2nd phalange of the index finger. However, triple gloving could not offer better protection than single gloving at the tip of ring finger.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

### 5.5 Contact Forces between Thumb and Index Finger for Tweezers Tasks

Edin et al. (1992) indicated that the finger-tip contact forces were about equal at the thumb and index finger when using a two-finger precision grip to lift object at equal frictional conditions for the two grip surfaces. The index finger must balance the force applied by the thumb to retain static equilibrium to resist pinch. With a similar two-finger posture during the tweezers task simulation in current study, no significant differences on means of contact forces between tip of thumb and index finger were found for the bare hand condition. However, when glovebox gloves were donned, the contact force at the tip of thumb was significantly higher (1.08 N) than at the tip of index finger even the frictional conditions were the same for both digits. Westling and Johansson (1984) stated that the factors that may affect finger-tip forces included friction, weight, safety margin factor (differences between the grip forces and the slip forces), and frictional conditions for previous trial. With the friction (same glove material in both digits) and weight (target task demand) controlled in this study, the safety margin factor and frictions for previous trial (not recorded in this study) may be the factors that cause the differences in the contact forces between the two digits when glovebox gloves were worn. Edin et al. (1992) also concluded that the finger-tip forces were independently controlled by each digit during precision grip lifting. The reasons could be due to the different responses from the mechanoreceptors in the skin of the thumb and index finger. Hence, other factors such as tactile perception differences between both fingers under gloved conditions and finger dexterity that may be correlated to safety margin were needed to be further evaluated.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## 5.6 Perceived Pain Threshold

There is no established guideline for assessing the evidence for causality between contact forces on the palmar skin and the development of MSDs in the hand and wrist. The magnitudes of contact forces can be compared with the perceived threshold of pain in the hand since pain is often a limiting factor during work with hand-held tools (Fraser 1980). Pain should also be taken seriously since it may be used as a warning signal and indicator of potential cell damage and death (Hardy et al. 1967). The pain-pressure threshold (PPT) data measured by Fransson-Hall and Kilbom (1993) on 64 points (Fig. 12) of the hand was used as the reference for pain indicator of the measured contact forces. Externally applied surface pressure (EASP) was exerted at an increasing rate of 25 kPa $s^{-1}$ (with 1.0 $cm^2$ aluminum contact area) and the level where the feeling of pressure turned into pain was recorded as PPT. The reported PPT ranges from the lowest 434 kPa at the thenar region (T13 in Fig. 12) to the highest 831 kPa at the second phalanx of the index finger.

Under bare hand conditions, the pressure levels measured in this study for roller tasks ranged from 13.2-21.5 % PPT, 13.2-24.7% PPT, 7.1-14.2% PPT, and 7.9-22.4% PPT at the tip of the thumb, 2nd phalange of the index finger, tip of the middle, and tip of ring fingers, respectively. For the tweezers tasks, the pressure levels measured in this study ranged from 9.5-30.4% PPT and 10.7-30.3% PPT at the tip of the thumb and index finger, respectively. For the wrench tasks, the pressure levels measured in this study ranged from 9.6-16.6% PPT, 8.6-21.6% PPT, 8.0-22.6% PPT, and 9.5-29.3% PPT at the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

tip of the thumb, 2nd phalange of the index finger, 2nd phalange of the middle finger, and at the H9 point of the palm region, respectively.

Under gloved hand conditions, the pressure levels measured in this study for roller tasks ranged from 13.0-37.1 % PPT, 13.9-34.5% PPT, 6.1-15.2% PPT, and 5.6-23.2% PPT at the tip of the thumb, 2nd phalange of the index finger, tip of the middle, and tip of ring fingers, respectively. For the tweezers tasks, the pressure levels measured in this study ranged from 9.8-46.3% PPT and 11.9-46.7% PPT at the tip of the thumb and index finger, respectively. For the wrench tasks, the pressure levels measured in this study ranged from 7.0-28.7% PPT, 7.7-25.0% PPT, 7.0-37.3% PPT, and 7.5-26.3% PPT at the tip of the thumb, 2nd phalange of the index finger, 2nd phalange of the middle finger, and at the H9 point of the palm region, respectively.

Fransson-Hall and Kilbom (1993) indicated that the sustained EASP estimated acceptable for a working day chosen by participated females and males subjects are 37 kPa and 104 kPa, respectively. In addition, when exposed to sustained EASP corresponding to 50% PPT for four selected measurement points, the feeling of pressure turned into pain within a couple of minutes where females experienced pain faster than males (74 s compared with 133 s). For repeated operations, the recommended pressure on the hand for manual exertions should not exceed approximately 20% of the measured female PPT and 25-50% of the measured male PPT. However, the authors also stated that the effects of repeatedly exposing the hand to EASP for an extended time should be further studied before any final recommendation can be accepted as guidelines for hand tool work.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The results of this study show that the pressure levels measured in this study are all lower than 50% of PPT reported by Fransson-Hall and Kilbom (1993). However, almost all the measured pressure levels are higher than the acceptable sustained EASP of females which corresponds to 8.5% PPT (37 kPa / 434 kPa). Higher task demands also resulted in pressure levels higher than the recommended 20% PPT for repeated operations. For these manual tasks, the tasks demands should be lowered or the tool can be designed to have larger contact areas, for example, width of the tweezers can be increased from 1.18 cm to1.5 cm (breadth at 1st joint of middle finger) and replace flat handle with round handle for roller, to minimize the pressure levels. In addition, the glovebox gloves can also be selected and designed based on the results of this study to lower the pressure levels to minimize the dosage (Pressure * Time) that may result in pain and potential cell damage and death.

### 5.7 Properties of Glove Materials

Batra et al. (1994) indicated that thickness, coefficients of static friction and pliability of glove materials are all significantly correlated to the grip strength measurements and the best two properties to link to grip strength are thickness and coefficients of static friction. For thickness and pliability properties, the present study did show significant correlation with grip strength. However, no correlation was found between coefficients of static friction and grip strength. This may be due to similar coefficients of static friction between different types of glove materials and between the same types of glove materials with different thickness used in this study.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

When performing tasks involving a gripping hand, material thickness and pliability parameters could be included for glove design and selection purposes since the interaction of thickness and pliability is a significant variable to predict maximum grip strength. The data collected from different studies could be further combined together to broaden the range of thickness and pliability values to increase the $R^2$ values for the grip strength predictive equations to better the design and selection of gloves to improve worker health and safety.

### 5.8 Guidelines Based on Subjective Effects

Assessing subjective variables such as tactility, tingling sensation, comfort, and preferences may encounter problems like reliabilities between raters and repeatability between tests. This study did not perform separate tip pinch tests and tool simulation tests between at least 48 hours time interval to examine reproducibility due to time constraints. In addition, no second rater besides the principal investigator participated to evaluate the reliability of the tactility results. Since the scores reported by different subjects for the same types of tasks and gloved conditions are reasonably consistent, these results on subjective variables are suitable and could be included for setting up the selection and design guidelines for glovebox gloves for females.

Burke et al. (1991) surveyed 2000 dentists and found that the principal reasons for not wearing gloves routinely were loss of tactile sensation and the discomfort associated with glove wearing. Since not wearing glovebox gloves is not an option to accomplish the desired hand protection in glovebox environment, it is imperative to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

design and select gloves that can minimize tactile reduction, tingling sensation, and discomfort.

No studies have evaluated the subjective effects of glovebox gloves on tactility, tingling, comfort, and preference. The results of the present study indicate that tingling sensation and discomfit scores and preference rank for all six glovebox gloves are significantly higher than that of bare hand. In addition, B30 and H30 gloves decreased the tactile performance significantly compared to the bare hand.

For the effects of glove material and thickness on tactility, tingling, comfort, and preference, the findings of the present investigation are:

(1) The butyl material performs better than hypalon and neoprene materials on tactility, tingling, and comfort. In addition, the subjects preferred butyl material rather than hypalon and neoprene materials.

(2) The thinner gloves retain better (lower scores) tactility, tingling, and comfort performances than the thicker gloves. In addition, the subjects preferred thinner gloves rather than the thicker gloves.

Good hand tactility is essential for hand function and any barrier on the hand can adversely affect the tactile perception of the hand. Tingling is one of abnormal nerve sensations (Shand's health care). One of the possible causes is due to continued and repeated pressure leading to numbness and nerve damage. In this study, tingling score was assessed after a 15-minute repeated tip pinch test. Higher tingling score could indicate higher repeated pressure on the palmar skin. Tingling with simple causes such

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

as pressing on a nerve is usually reversible, however, continued nerve damage can lead to numbness.

To maintain tactility, reduce the tingling sensation and discomfort during glovebox gloves usage, butyl material could be selected if other criteria (such as chemical, physical, biological etc) were met since it could offer better performance for these subjective effects. Thinner gloves could be used to retain better tactility, tingling, and comfort performances. At the same time, the preference needs of the subjects could be satisfied.

### 5.9 Guidelines Based on Tendon and Muscle Forces Results

The effects on tendon and muscle forces were similar to that of the effects of gloves on contact forces with small variations in minor components. The similar results with small variations could be attributed to small variations of joint positions (angles) of the fingers and the thumb when holding the tools, to the different length of digits among subjects, and to different moment and force potentials among tendons and muscles. The only available direct measurements of in vivo tendon forces were reported by Bright and Urbaniak (1976) where flexor tendon tension for the FP was found to be in the ranges of 2.5-12.5 kg (24.5-122.6 N) and 4.0-20.0 kg (39.2-196.1 N) in tip pinch and grasp hand functions, respectively. Compared to roller and wrench tasks, the values are relatively higher than the theoretical estimated results shown in the present study. For tweezers tasks, the tendon forces predicted in FP of this experiment fell into the ranges of 2.5-12.5 kg (24.5-122.6 N) in tip pinch hand function reported by Bright and Urbaniak (1976).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reliable verification of the theoretical results presented here awaits the development of better biomechanical models or experimental methods.

For the effects of glove on the tendon and muscle forces, the results (Table 26) of the present study show that various gloves increased the forces significantly compared to bare hand in TE, FP, RB, UB, RI, and LU of the index finger for roller tasks, and in APB of the thumb and in FP and RI of the index finger for tweezers tasks. Neoprene gloves in 0.03" thickness also increased the forces significantly in TE, FP, RB, UB, RI, and LU of the middle finger for wrench tasks. In addition, N30 glove increased the forces in TE, RB, and UB of the index finger for tweezers tasks. On the contrary, H15 glove decreased the forces significantly compared to bare hand in TE, FP, RB, and UB of the ring finger for roller tasks. B30, H15, H30, N15, and H30 gloves also decreased the forces significantly compared to bare hand in RI of the ring finger for roller tasks.

For the effects of glove material, layer, and thickness on tendon and muscle forces, the findings of the present investigation are:

(1) Hypalon material reduced the forces significantly compared to neoprene material in TE, FP, RB, and UB of the ring finger for roller task. Hypalon material also reduced the forces significantly compared to butyl material in FPL, APB and ADD of the thumb for wrench tasks. In addition, hypalon material reduced the forces significantly compared to butyl material in APB and ADD of the thumb for tweezers tasks.

(2) Triple layers decreased the forces significantly compared to double layers in FPL, APB and ADD of the thumb, in TE, FP, RB, UB, RI, and LU of the index finger, and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

in RI of ring finger for roller tasks. Triple and double layers also decreased the forces significantly compared to single layer in FPL of the thumb for tweezers tasks. In addition, triple layers decreased the forces significantly compared to single and double layers in FPL, APB, and ADD of the thumb for wrench tasks.

(3) Thinner gloves decreased the forces significantly compared to thicker gloves in APB and ADD of the thumb for tweezers tasks.

To minimize the mechanical stress (optimize protection) on tendons and muscles of the hand, hypalon material could be selected if other criteria (such as chemical, physical, biological etc) were met since it could offer protection for specific hand digits (thumb and ring finger) with the lowest tendon and muscle forces recorded. Thinner gloves could be used to reduce the tendon and muscle forces of the thumb. In addition, triple gloving could be used to lower the tendon and muscle forces of the thumb, the index and ring fingers.

### 5.10 Selection and Design Guidelines in General

Table 32 shows the summary of the supported ergonomics guidelines to select and design glovebox gloves for females based on "minimizing effects on hand performances" and "optimizing protection" criteria. The design/selection guidelines based on minimizing effects on hand performances were shown in Chapters 5.2, 5.3, and 5.8. The design/selection guidelines based on optimizing protection were shown in Chapters 5.4 and 5.9.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Table 32 Summary of selection and design guidelines for glovebox gloves for the eleven (ten for roller and wrench) female subjects

| | | Thickness | | Layer | | | Material | |
|---|---|---|---|---|---|---|---|---|
| **Performances** | | **Best** | **Best** | **Medium** | **Worst** | **Best** | **Medium** | **Worst** |
| Grip | | 1 | 1 | 2 | 3 | B, H* | | N |
| Pinch | | 1 | ** | | | ** | | |
| Subjective | | | | | | ** | | |
| -Tactility | | 1 | --- | --- | --- | B | | H, N |
| -Tingling | | 1 | --- | --- | --- | B | H | N |
| -Comfort | | 1 | --- | --- | --- | B | | H, N |
| -Preferences | | 1 | --- | --- | --- | B | | H, N |
| **Contact Forces** | | | | | | | | |
| Roller | Thumb (Tip) | ** | 3, 1 | | 1, 2 | ** | | |
| | IF (2nd Ph) | ** | 3, 1 | | 1, 2 | ** | | |
| | MF (Tip) | 1 | 3, 1 | | 1, 2 | H, B | | B, N |
| | RF (Tip) | 1 | 1 | | 2, 3 | H | B | N |
| Tweezers | Thumb (Tip) | 1 | 3, 2 | | 2, 1 | N, H | | H, B |
| | IF (Tip) | ** | 3 | | 1, 2 | ** | | |
| Wrench | Thumb (Tip) | ** | 3 | | 2, 1 | H, N | | N, B |
| | IF (2nd Ph) | ** | ** | | | ** | | |
| | MF (2nd Ph) | ** | ** | | | ** | | |
| | HT | ** | ** | | | ** | | |
| **Tendon and Muscle Forces** | | | | | | | | |
| Roller | Thumb | ** | 3, 1 | | 1, 2 | ** | | |
| | IF | ** | 3, 1 | | 1, 2 | ** | | |
| | MF | ** | ** | | | ** | | |
| | RF | ** | 3, 1 | | 1, 2 | H, B | | B, N |
| Tweezers | Thumb | 1 | 3, 2 | | 1 | H, N | | N, B |
| | IF | ** | ** | | | ** | | |
| Wrench | Thumb | ** | 3 | | 1, 2 | H, N | | N, B |
| | IF | ** | ** | | | ** | | |
| | MF | ** | ** | | | ** | | |

* If two items were placed in the same cell, no significant differences were found between these two items.

** No significant differences were reported

--- Not applicable

Thickness: 1 (0.015"); 2(0.03")

Layer: 1 (single); 2 (double); 3 (triple)

Material: B (butyl); H (hypalon); N (neoprene)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Following is the recommended design/selection guideline of thickness, glove material, and number of layers for all three tools to meet both criteria. Based on the first criterion, the thickness of the gloves to be donned is recommended as 0.015" to minimize grip and key pinch strength degradation, to minimize tingling sensation, and to maintain good tactile perception and comfort. In addition, the female subjects preferred thinner gloves rather than thicker gloves. To satisfy the second criterion, the recommended thickness of the gloves to be used is also 0.015" for roller tasks to reduce the contact forces at the tip of middle and ring fingers. In addition, 0.015" thickness gloves could reduce the tendon and muscles force in the thumb for tweezers tasks. To optimize protection without compromising the effects on hand performances or vice versus, the thickness of the glove is going to be 0.015".

In terms of glove material, the first criterion indicated that butyl and hypalon materials could be selected because of their smallest grip strength degradation compared to bare hand if other criteria (chemical, physical, biological etc) are met. Butyl material also performs better than hypalon and neoprene materials on tactility, tingling, and comfort. In addition, the subjects preferred butyl material rather than hypalon and neoprene materials. The second criterion suggested that the hypalon material could be selected to reduce the contact forces at the tip of the thumb (wrench task) and at the tip of the middle and ring fingers (roller task). Hypalon material could also be used to reduce the tendon and muscle forces of the thumb (tweezers and wrench tasks) and the ring finger (roller task) if other criteria (chemical, physical, biological etc) are met. When considering both criteria for the manual operations of all three tools, the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

recommended glove material are contradictory. To select a glove for immediate use, hypalon material could be picked to meet the optimizing protection criteria and at the same time retain the grip and key pinch strength capabilities. However, the subjective hand performances could be compromised. To design a new glove for all three tools, use butyl as base glove material except at the tip of the thumb and tip of the middle and ring finger regions where hypalon material are favored as base material. This design could minimize the effects on hand performances and reduce the contact and tendon and muscle forces to optimizing protection at the same time. However, this design recommendation still needs to be validated in advance and the cost for manufacturing this glove should be evaluated.

In terms of gloving conditions, the first criterion indicated that single gloving could be used to minimize the effects on maximum grip strength. The second criterion suggested that triple gloving could be selected with the lowest contact forces and forces in tendons and muscles for the manual operations of all three tools except at the tip of the ring finger where single gloving is favored. Napier (1956) classified the prehensile movements of the hand into two discrete patterns: precision grip and power grip. In a power grip posture, the object may be held in a clamp formed by the partly flexed fingers and the palm and counter pressure being applied by the thumb lying more or less in the plane of the palm. In a precision grip posture, the object may be pinched between the flexor aspects of the fingers and the opposing thumb. The grip strength grip and roller and wrench grips are categorized as power grips while the tweezers grip reflects a precision grip in the present study. To meet both criteria for roller tasks, single gloving

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

could be adopted to minimize grip strength reduction. At the same time, the contact and tendons and muscles forces could be lowered since no significant differences were found between triple and single gloving conditions. To select number of layers for immediate use for tweezers tasks, triple gloving should be adopted to minimize the contact and tendon and muscle forces since precision grip plays greater role than power grip. For wrench tasks, the hand is a power grip and the single gloving condition could be adopted since the triple gloving only performed better on contact and tendons and muscles forces than single gloving at the tip of the thumb. To select number of layers for immediate use when considering roller and wrench tasks together, single gloving should be adopted. When considering all three tasks together to select number of layers for immediate use, the decision to select single or triple gloving should depend on majority length of time which is spent for tweezers or roller and wrench tasks.

To recommend a design guideline of gloving condition, “selective protection” principle proposed by Muralidhar et al. (1999) could be adopted to meet both criteria at the same time. Those authors designed an ergonomic glove with adequate protection in certain regions and minimal glove material in other regions. Two sets of prototype gloves, one with two layers of protection and the other with four layers of protection were fabricated with two and four layers of glove material attached on certain regions of the glove to the base material (single layer cotton jersey glove) by means of flexible fabric glue. The results indicated that the both prototype gloves showed an improvement in grip strength over that of the double glove. When applying the “selective protective” principal to the present study, one layer of cotton material and one layer of natural

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

rubber material can be attached inside the glovebox glove at the tip of the thumb and the tip of index finger regions. Then the one layer glove with selective protective will satisfy the first criteria. In addition, the contact and tendon and muscle forces could be kept to minimum at the tip of the thumb and the tip of index finger for tweezers tasks and at the tip of thumb for wrench tasks. The principle is to use different amounts of protective material selectively over certain critical regions of the hand to better glove design. However, this design recommendation still needs to be validated in advance and the cost for manufacturing this glove should be evaluated.

### 5.10.1 Computer Program for Design/Selection of Glovebox Gloves

A "Glovebox Gloves Design/Selection" software package was programmed and compiled using Microsoft Visual Basic 6.0 to facilitate the design and selection of glovebox gloves using the results of the present study. The interface is user friendly and completely event driven.

When the program is initiated, the user is prompted (Figure 33) to specify tool (s) to "Find the Best Glove Design" or to "Select the Glove to Use Immediately". Then, the subject can select one, two, or three tools for design or quick selection purpose. Figure 34 shows the best glove design guideline for roller based on the results of the present study. To design the best glove for roller, use 0.015" butyl as base glove material except at the tips of the middle and ring finger regions where 0.015" hypalon material are favored as base material. Single layer should be used and one layer of cotton material and one layer of natural rubber material could be attached inside the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

glovebox glove at the tip of the thumb and at the 2nd phalange of the index finger regions to reduce the contact and tendon and muscle forces.

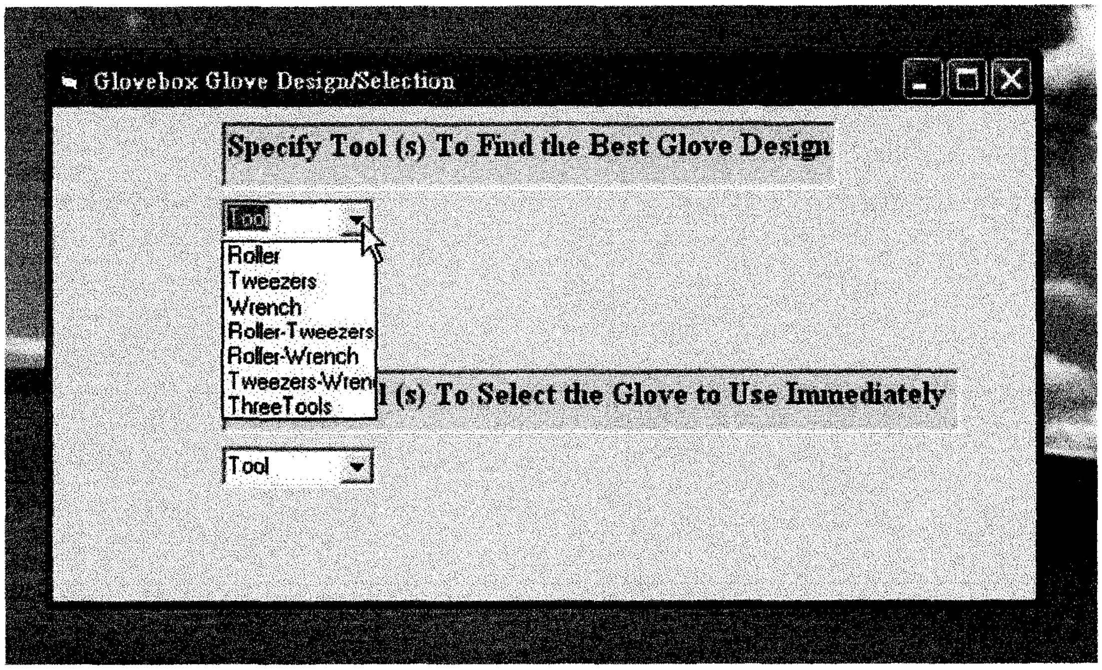
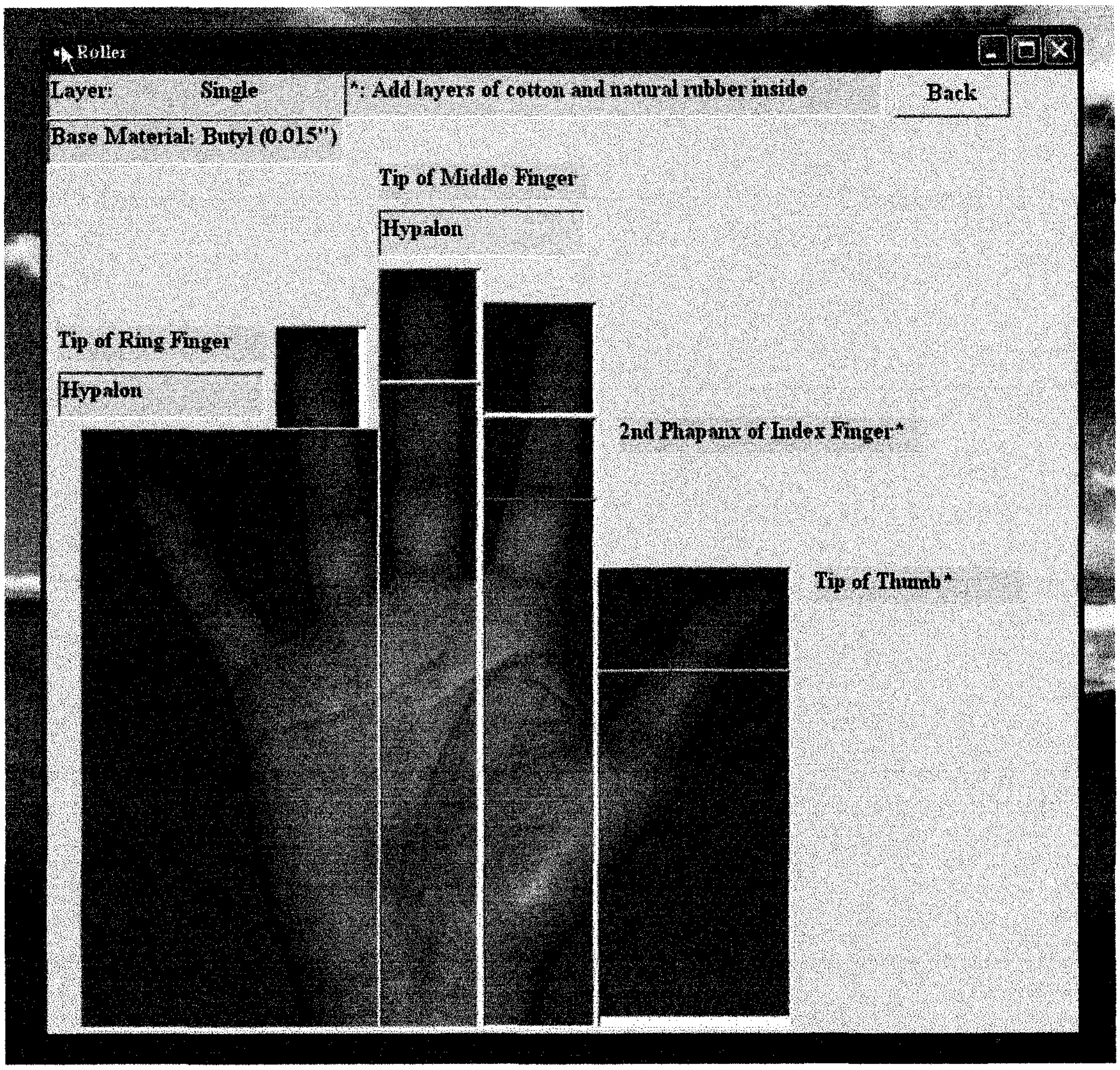


Figure 33 GloveBox glove design/selection program

### 5.10.2 Test Protocols to Be Adopted

For potential glove material, the interaction of thickness and pliability properties of glove could be used to predict the grip strength reduction from the bare hands. Glove designers and manufacturers could also adopt grip and key pinch strength tests (using Jamar dynamometer and Jamar pinch meter) to evaluate strength degradation, 2PD test to evaluate tactility, Borg10 scale to evaluate discomfort and tingling, and FSRs technology to evaluate the contact forces on the palmar skin as testing protocols for a new glove product.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.



Layer: Single

*: Add layers of cotton and natural rubber inside

Base Material: Butyl (0.015")

Tip of Middle Finger: Hypalon

Tip of Ring Finger: Hypalon

2nd Phapanx of Index Finger*

Tip of Thumb*

**Figure 34 The best glove design guideline for roller based on the results of the present study.**

### 5.11 Glove/Hand Fit

Two hand sizes of glovebox gloves, 8.5"and 9.75", were provided and the subject wore both of the gloves to pick the best fit glove. All eleven female subjects picked the 8.5" glove which is the smallest size available of glovebox gloves. Separate one-sample

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

T test were performed to compare the difference in the length of circumference, length of thumb and fingers between the glovebox glove and the hand of the subject. The results (Table 33) show that the circumference of the glove (215.9 mm) is significant longer (mean difference = 10.4 mm) than the circumference of the hand of the subjects (t = -3.069, $p<0.05$). The length of the thumb and fingers of the glove are also significantly longer than the length of the thumb and fingers of the subjects. The gloves do not seem to fit the hands of the female subjects well. The published literatures (Kovacs et al. 2002) indicated that oversized gloves impair grip strength. Therefore, better fitting glovebox gloves could increase the grip strength of the subjects. In terms of pinch strength and palmar contact force, the effects of glove material, thickness, and number of layers are more important factors than the glove/hand fit. The reason is that the forces were exerted and measured at the contact points.

**Table 33 One-sample T test between glovebox glove and the hand of subject for the circumference, length of thumb and fingers**

| | Circumference | Thumb | IF | MF | RF | LF |
|---|---|---|---|---|---|---|
| **T** | -3.07 | -16.79 | -7.05 | -9.9 | -6.37 | -14.29 |
| **Sig. (2-tailed)** | 0.012 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Mean Difference (mm)** | -10.4 | -14.2 | -5.6 | -8.6 | -4.8 | -13.1 |

### 5.12 Effect of Glove Age and Dexterity

Tensile strength, elasticity/elongation, and tear and puncture resistance of gloves may be affected by glove age (Lawrence Berkeley National Laboratory). Therefore, the effects of tensile strength, elasticity/elongation, and tear and puncture resistance of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

gloves on hand performance and mechanical stress could be further studied to relate the effect of glove aging on hand performance and mechanical stress.

Dexterity is a hand function referring to the ability of the individual to manipulate objects with their hands (ASTM F2010). In most ergonomics studies, dexterity is quantified and measured based on the time or the error rates it takes to complete a task. Less time and fewer errors imply better dexterity. Several studies had investigated the effects of gloves on hand dexterity and gloves have been found to reduce dexterity (Plummer et al. 1985; Bensel 1993; Bishu and Klute 1995). Glovebox gloves were shown to increase contact force significantly compared to bare hand at the tip of index finger for tweezers tasks (Chapter 4.5). Glovebox gloves are also expected to reduce dexterity for tweezers operations compared to bare hands. If the objective of the tweezers task is to satisfy the task demand, then, the hand dexterity (time to complete task) could be comprised and vice versa. Further study is needed to correlate the dexterity and contact force during tweezers task operations.

## 5.13 Relevance to Males, Left-Handed Users, and Other Non-Glovebox Gloves

Chapter 5.2 showed that the effects of glovebox gloves on maximum grip strength were similar to that of female subjects. Male hands may fit into the glovebox gloves better than females. However, the goodness of fit did not affect grip strength which is the only dependent variable reported to be affected by the oversized gloves (Kovacs et al. 2002). Therefore, the effects of glovebox gloves on hand performances and mechanical stress should still be similar to that of females.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Mathiowetz et al (1985) showed that the grip strength and key pinch strength of left and right hand-dominant subjects were not statistically significant different. No literature was found that showed anatomical differences between the dominant right hand and the dominant left hand. In addition, glove/hand fit may not affect hand performance and mechanical stress even if the fit is different. Therefore, the effects of glovebox gloves on hand performance and mechanical stress for left hand users should be similar to that of right hand users. The factor that could affect the hand performance and mechanical stress is the task position if it had not been adjusted accordingly to facilitate the operation of left-hand users.

For non-glovebox gloves, if the glove thickness falls with 0.015" to 0.03", the thickness effect of the non-glovebox gloves on hand performance and mechanical stress should be similar to that of glovebox gloves. The effect of number of layers should also be similar when performing the same performance tests and simulated task. Glove material did affect grip strength, subjective hand performance, and mechanical stress as shown in the present study. The effects of non-glovebox gloves on hand performance and grip strength should be similar to that of glovebox gloves. The present study showed that the interaction of thickness and pliability could be used to predict grip strength degradation relative to the bare hands. However, glove properties measured in this study did not correlate significantly with key pinch strength and contact forces. Therefore, glove properties other than those measured in this study could be further explored to find significant correlation with hand performance and mechanical stress.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

# Chapter 6

## Conclusions

The first goal of this study was to (1) evaluate the effect of glove on hand performances, (2) evaluate the effects of glove and task demand on mechanical stress, (3) evaluate the effects of glove material, thickness, and layer on hand performances, and (4) evaluate the effects of glove material, thickness, layer, and task demand on mechanical stress. For the glove factor, the null hypotheses (1) for maximum grip strength, tactility, tingling, discomfort, and preference were rejected. The gloves decrease maximum grip strength, decrease tactility, and increase discomfort compared to bare hand. The subjects also prefer bare hands to the gloved hands. The null hypotheses (1) for contact forces and tendon and muscle forces were rejected at the index and ring fingers for the roller tasks, at the thumb and index finger for tweezers tasks, and at the middle finger for wrench tasks. Gloved hands increased the mechanical stress compared to bare hand except at the ring finger for roller tasks where gloved hand decrease the mechanical stress compared to bare hand.

For the glove material factor, the null hypotheses (2) for maximum grip strength, tactility, tingling, comfort, and preference were rejected. The butyl and hypalon materials retain better grip strength compared to the neoprene material. The butyl material performed better in subjective hand performance than the hypalon and neoprene materials. The null hypotheses (2) for contact forces and tendon and muscle forces were rejected at the middle and ring fingers for roller tasks and at the thumb for tweezers and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

wrench tasks. Hypalon material decreased the mechanical stress compared to neoprene material at the middle and ring fingers for roller task. Hypalon material also decreased the mechanical stress compared to butyl material at the thumb for wrench tasks. In addition, neoprene material decreased the mechanical stress compared to butyl material at the thumb for tweezers tasks.

For the thickness factor, the null hypotheses (3) for all of the hand performances were rejected. Thin (0.015") gloves retain better grip and key pinch strength, tactility, tingling, preference, and less discomfort compared to thick (0.03") gloves. The null hypotheses (3) for contact forces and tendon and muscle forces were rejected at the middle and ring fingers for the roller tasks and at the thumb for tweezers tasks. Thin gloves decreased mechanical stress compared to thick gloves at the middle and ring fingers for the roller tasks and at the thumb for tweezers tasks.

For the gloving condition, the null hypotheses (4) for maximum grip strength and for mechanical stress at all the contact areas for roller and tweezers tasks and at the thumb for wrench tasks were rejected. Single layer retain better grip strength compared to double and triple layers. Single layer also decreased mechanical stress compared to double and triple layers at the ring finger for roller tasks. However, triple layers decreased mechanical stress compared to double layers at the thumb, index finger, and middle finger for roller tasks. Triple layers also decreased mechanical stress compared to single layer at the thumb for tweezers and wrench tasks.

The second goal of this study was to develop ergonomics design/selection guidelines for glovebox gloves based on the "minimizing effects on hand performances"

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

and "optimizing protection" criteria. When applying both criteria on the results of this study, the recommended quick selection guideline for three tools is to use 0.015" hypalon glove to meet the optimizing protection criteria and at the same time retain the grip and key pinch strength capabilities. The decision to select single or triple gloving depends on the majority length of time which is spent for tweezers (triple layers) or roller and wrench tasks (single layer). However, subjective hand performances could be compromised to select a glove for immediate use. The best design guideline recommended for three tools is to use 0.015" butyl as base glove material except at the tip of the thumb and the tip of the middle and ring fingers where hypalon material is the preferred material for those hand regions. One layer of glove should be selected while one layer of cotton and one layer of natural rubber material could be added at the tips of thumb, index finger, and middle fingers and at the 2nd phalanx of the index finger. This design could minimize the effects on hand performances and reduce the mechanical stress while optimizing protection. The "Glovebox Design/Selection" software package has also been created according to the results of this study to facilitate finding the "best design" and "quick selection" guidelines for an individual tool or combination of two or three tools. These recommended guidelines could accomplish the desired hand protection against the force risk factor that could cause musculoskeletal disorders in the hand and create a safer workplace for the female workers.

When applying the recommended quick selection and best design guidelines for glovebox gloves, hazards evaluation should be performed first to identify if both the base and selected protective glove materials meet the chemical, physical, biological or

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

other required criteria. The selected protective material should also be compatible with the base glove material. In addition, the efficacy of the proposed design could be further validated to meet the requirements.

For potential glove materials, the interaction of thickness and pliability of glove could be used to predict the grip strength reduction relative to the bare hands. Glove designers and manufacturers could also adopt grip and key pinch strength tests (using Jamar dynamometer and Jamar pinch meter) to evaluate strength degradation, the 2PD test to evaluate tactility, the Borg10 scale to evaluate discomfort and tingling, and the FSRs technology to evaluate the contact forces on the palmar skin as testing protocols for a new glove product. In addition, the data collected in this study have potential value for tools and tasks improvement. A practical application is to design the high force-bearing area of a tool to span the breadth of the thumb or finger (e.g. span of thumb for the wrench tool). This will maximize the contact area between the hand and tool to reduce the force amplitude. The tasks could also be designed with lower tasks demands to prevent repetitive risk factors associated with development of musculoskeletal disorders.

An extension of the present work would be to obtain similar information (e.g. the critical areas) for other tools used for glovebox works. The subjects recruited in the present study are female students or housewives without working experience with gloveboxes. Male subjects and subjects with glovebox working experience should be recruited. Thickness level could be increased. Lab simulations were conducted around the center of the glovebox which is the easiest position to perform the glovebox works.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

As the position of the task deviates from the optimal location, force endured by the glove and mechanical stress may increase. Potential glove materials and wider ranges of glove properties could be included. The effects of glove fit could be further investigated if better standard methods are available. A glovebox used for nuclear material operations usually maintained at a pressure of 0.5" to 1" of water negative to the ambient. Lab simulations could also be performed in negative pressure environments. Glove age known to affect tensile strength, elasticity/elongation, and tear and puncture resistance could be further studied. In addition, the effects of gloves on other hand performance parameters such as dexterity, wrist deviations, and ranges of motion, etc could be further investigated to facilitate the design and selection of glovebox gloves to better health and safety for glovebox environments.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 1 UCLA IRB Approval

---

# APPROVAL NOTICE

OFFICE FOR PROTECTION OF RESEARCH SUBJECTS
2107 Ueberroth Building
169407

DATE: January 22, 2003

TO: Peng-Cheng Sung, MS
Principal Investigator

FROM: Keith T. Kernan, Ph.D.
Chair, General Campus Institutional Review Board

RE: UCLA IRB #G01-11-015-02
**Approved by Expedited Review**
**(Approval Period from** 01/22/2003 **through** 01/21/2004)
Glovebox Gloves: Effects on Hand Performance and Development of Design Guidelines

Please be notified that the UCLA Institutional Review Board (UCLA IRB) has approved the above referenced research project involving the use of human subjects in research. The UCLA's Multiple Project Assurance (MPA) with the National Institutes of Health, Office for Protection from Research Risks is M-1127.

**PLEASE COMPLY WITH THE FOLLOWING CODICIL(S) IMPOSED BY THE HSPC:**

1. **This approval is issued for the pilot phase of this study only. The procedures and study materials for future phases of this study must be submitted to the UCLA GC-IRB for review and approval prior to implementation.**

Keith T. Kernan

Approval Signature of the UCLA IRB Chair

**PRINCIPLES TO BE FOLLOWED BY PRINCIPAL INVESTIGATORS:**

As the Principal Investigator, you have ultimate responsibility for the conduct of the study, the ethical performance of the project, the protection of the rights and welfare of human subjects, and strict adherence to any stipulations imposed by the UCLA IRB. You must abide by the following principles when conducting your research:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1. Perform the project by qualified personnel according to the approved protocol.
2. Do not implement changes in the approved protocol or consent form without prior UCLA IRB approval (except in a life-threatening emergency, if necessary to safeguard the well-being of human subjects.)
3. If written consent is required, obtain the legally effective written informed consent from human subjects or their legally responsible representative using only the currently approved UCLA-IRB stamped consent form.
4. Promptly report all undesirable and unintended, although not necessarily unexpected adverse reactions or events, that are the result of therapy or other intervention, within five working days of occurrence. All fatal or life-threatening events or events requiring hospitalization must be reported to the UCLA IRB in writing within 48 hours after discovery.
5. In clinical medical research, any physician(s) caring for your research subjects must be fully aware of the protocol in which the subject is participating.
6. No subjects may be identified, contacted, recruited, or enrolled until the contract with the sponsor is finalized by the University.

**FUNDING SOURCE(S):**

According to the information provided in your application, the funding source(s) for this research project may include the following: extramural.

| | |
|---|---|
| PI of Contract/Grant: | Peng-Cheng Sung |
| Funding Source: | NIOSH |
| Contract/Grant No: | t42/cct918726-02 |
| Contract/Grant Title: | Glovebox Gloves: Effects on Hand Performance and Development of Design Guidelines |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 2 Letter of Informed Consent

University of California, Los Angeles

# CONSENT TO PARTICIPATE IN RESEARCH

Glovebox Gloves: Effects on Hand Performance and Development of Design Guidelines

You are asked to voluntarily participate in a research study conducted by Peng-Cheng Sung, M.S., and William Hinds, SC.D. from the Environmental Health Science department at the University of California, Los Angeles. The results will be contributed to Peng-Cheng Sung's Ph.D. dissertation. You were selected as a possible participant in this study because you do not have previous hand or finger injuries. If you are a student at UCLA, your decision about whether or not to participate in the study will in no way affect your grades or your relationship with UCLA.

- **PURPOSE OF THE STUDY**

The primary goal of this proposed study is to evaluate the effects of gloves used for glovebox work on hand performance and contact forces. In addition, this proposed study will develop ergonomics design guidelines of glovebox gloves through gloves evaluation and laboratory tasks simulation to optimize the protection without compromising workers' hand performance.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:

Prior to start of the tasks simulation:
1) We will measure your height, weight, and hand dimensions.
2) You will stand straight in front of glovebox with forearm of dominant hand rested in the glovebox floor and grasp Jamar pinch strength meter with maximum force for bare and gloved hands. Then, a steel shaft will be fixed horizontally on top of Futek torque sensor which is secured on the glovebox floor. You will be instructed to pull and then push the steel shaft toward and away from you with maximum hand force without body movement.
3) We will measure your tactile perception with your vision occluded and the dominant hand (with and without glove) supported securely to avoid movement. One or two points of test instrument (Disk Criminator) will be randomly applied to your hand. You will be asked to report whether you can feel one or two points touching skin.

During the tasks simulation:
You will use five hand tools (a ball-pin hammer, a roller, a screwdriver, a crescent wrench, and a pair of tweezers) with bare and gloved hands to perform laboratory tasks simulation conducted inside a glovebox to determine the wrist deviations and contact forces. You are required to control the exertion force within ±10% of the target task demand according to a digital readout displaying on the screen of a computer monitor during the test.

UCLA IRB #G01-11-015-02
Expiration Date: January 21, 2004

APPROVED
JAN 22 2003
UCLA GENERAL CAMPUS
INSTITUTIONAL REVIEW BOARD

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1) To simulate hammer task, you will
    a) Raise the hammer above shoulder height.
    b) Hit the hammer on top of steel plate supported by force sensors located on the center of glovebox floor with 10, 30 and 50 Newton (N) target forces.
2) To simulate roller task, you will
    a) Roll the roller back and force on top of polycarbonate plate supported by force sensors located on the center of glovebox floor with 10, 20 and 30 N target forces.
3) To simulate screwdriver task, you will
    a) Use screwdriver to turn the screw fixed on the torque sensor located on the center of the glovebox floor with 5, 10 and 15 N target forces.
4) To simulate wrench task, you will
    a) Use crescent wrench to turn the nuts fixed on the torque sensor located on the center of the glovebox floor with 10 and 20 N target forces.
5) To simulate tweezers task, you will
    a) Use a pair of tweezers to carry a 33.7 gm rectangular polycarbonate plate for 5 cm from right to left on the center of the glovebox floor with 5, 10 and 15 N force exertions.

This is a randomized study. This means that the simulation tasks for five hand tools will be presented to you randomly. It will take ten two-hour sessions for you to complete the study. During the test, you will have 5 minutes rest after every 25 minutes test. The procedures will be performed at UCLA Ergonomics Laboratory located at A4-158 Warren Hall.

- **POTENTIAL RISKS AND DISCOMFORTS**

Minor hand and finger discomfort may be experienced while participating in this study. You may choose at any time to discontinue the test should the discomfort become unbearable.

- **POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY**

The knowledge of the glove effects on hand performance and the developing ergonomics design guidelines of glovebox gloves may benefit glove designers and manufacturers and workers using gloves. It may also benefit other researchers concentrating in this field and members of the public who use gloves. You will not directly benefit from your participation in this study.

- **PAYMENT FOR PARTICIPATION**

There is no compensation of any form for your participation in the study.

UCLA IRB #G01-11-015-02
Expiration Date: January 21, 2004

**APPROVED**
JAN 2 2 2003
UCLA GENERAL CAMPUS
INSTITUTIONAL REVIEW BOARD

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.

A coded identifier will be assigned to you for data collection and a key will be used to link your name to the coded identifier. The data will be stored associated with coded identifiers using a 486-DX computer. The key will be kept in a locked filing cabinet. Only the principal and co investigators can get access to this computer, this locked filing cabinet, the coded identifiers and the key. When the research has been completed, the data will be published to peer-reviewed journal. The coded identifiers and key will not be released and the key will be destroyed after completion of this study.

- **PARTICIPATION AND WITHDRAWAL**

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so. If you feel pain and have skin injuries during the test, we will terminate your participation.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact

Peng-Cheng Sung, M.S.
10833 Le Conte Avenue, 56-070
Los Angeles, CA 90095-1772
(310) 467-4052

William Hinds, SC.D.
10833 Le Conte Avenue, 56-071B
Los Angeles, CA 90095-1772
(310) 825-7152

- **RIGHTS OF RESEARCH SUBJECTS**

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact the Office for Protection of Research Subjects, 2107 Ueberroth Building, UCLA, Box 951694, Los Angeles, CA 90095-1694, (310) 825-8714.

UCLA IRB #G01-11-015-02
Expiration Date: January 21, 2004

APPROVED
JAN 22 2003
UCLA GENERAL CAMPUS
INSTITUTIONAL REVIEW BOARD

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## SIGNATURE OF RESEARCH SUBJECT

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

Name of Subject ____________ Date ____________

Signature of Subject ____________ Date ____________

## SIGNATURE OF INVESTIGATOR

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

Signature of Investigator ____________ Date ____________

UCLA IRB #G01-11-015-02
Expiration Date: January 21, 2004

APPROVED
JAN 22 2003
UCLA GENERAL CAMPUS
INSTITUTIONAL REVIEW BOARD

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 3 Instructions to Subject for Using the Borg's CR-10 Scale on Tingling Sensation and Comfort

You are looking at a scale that contains a number from 0 to 10. We use this scale so that you may translate your feelings of tingling (discomfort) into numbers after the tip pinch exercise. The range of numbers should represent a range of feeling from "no tingling (discomfort) at all to "maximal tingling (discomfort)". In order to help you select a number that corresponds to your subjective feelings, verbal expressions have been attached to most of the numbers. For example, 0.5 is associated with feelings of "very, very weak" tingling (discomfort), while 10 is associated with feelings of "very, very strong" tingling (discomfort). Your goal is to rate your feelings which are caused by the exercise.

We will ask you to specify the feelings by selecting a number that most accurately corresponds to your perception of the tingling feelings. Each response will then be recorded on your individual data sheets. Keep in mind that there are no right and wrong numbers. Use any number you think is appropriate.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 4 Microsoft Visual Basic Code for Estimating Tendon and Muscle Forces

```
'Define Global variables
Global Matrix_Thumb(1 To 18, 1 To 18) 'Matrix of Thumb with dimensions 18x18
Global Matrix_Finger(1 To 126, 1 To 19, 1 To 19) '126 combinations of Matrix of other Fingers with dimensions 19x19
Global Triangular_Thumb(1 To 18, 1 To 19) 'Triangularized Matrix Thumb
Global Triangular_Finger(1 To 126, 1 To 19, 1 To 20) 'Triangularized Matrix Finger
Global Array_Thumb(1 To 18) 'Array of the constants of Thumb
Global Array_Finger(1 To 19) 'Array of the constants of Fingers
Global Solution_Thumb(1 To 18) 'Array of the Solutions of Thumb
Global Solution_Finger(1 To 126, 1 To 19) 'Array of the Solutions of Finger, there are 126 possible solutions combinations
Global Solution_Problem_Thumb As Boolean 'Determine whether the system was solved or not for Thumb
Global Solution_Problem_Finger(1 To 126) As Boolean 'Determine whether the system was solved or not for Finger
Global Solution_Problem_index As Integer 'Marked which combination of finger can not be solved
Global Solution_Validity_Thumb As Boolean 'Determine if the solution meet the selection criteria from journal for Thumb
Global Solution_Validity_Finger(1 To 126) As Boolean 'Determine if the solution meet the selection criteria from journal for finger
Global Division_Tri_Matrix_Thumb As Boolean 'To verfify that the division of triangular matrix is not zero
Global Division_Tri_Matrix_Finger(1 To 126) As Boolean 'To verfify that the division of triangular matrix is not zero
Global xlApp As Excel.Application
Global xlBook As Excel.Workbook
Global xlSheet As Excel.Worksheet

Private Sub Form_Load()
        'Let the user to select the finger from the combo box
            Combo1.AddItem "Thumb"
            Combo1.AddItem "IndexFinger"
            Combo1.AddItem "MiddleFinger"
            Combo1.AddItem "RingFinger"
            Combo1.AddItem "LittleFinger"
End Sub

Private Sub cmdSOLVE_Click()
            Call Build_Matrices
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
      If Combo1.Text = "Thumb" Then
        Call Build_Triangular_Matrix_Thumb
        If Solution_Problem_Thumb = False Then
          Call Back_Substitution_Thumb
          If Division_Tri_Matrix_Thumb = True Then
            Call Solutions_Excel_Thumb
          Else
            MsgBox "No solutions found"
          End If
        Else
          MsgBox "No solutions found"
        End If
      Else
        For i = 1 To 126
          Solution_Problem_index = i
          Solution_Validity_Finger(Solution_Problem_index) = False 'set
    every solution to false first
          'Division_Tri_Matrix_Finger(Solution_Problem_index) = True
    'suppose the division is not zero and will check during back_substitution
          Call Build_Triangular_Matrix_Finger
          If Solution_Problem_Finger(i) = False Then  'check if determinant
    = 0
            Call Back_Substitution_Finger
            If Division_Tri_Matrix_Finger(Solution_Problem_index) = True
    Then
              Call Validity_Check_Finger 'use this to check the validity and
    get the exact solution
              ‘Solution_Validity_Finger(i) = True  'use this to see all
    possible solutions with validity check
            End If
          End If
        Next i
        Call Solutions_Excel_Finger
      End If
      'close the workbook
      'xlApp.Workbooks.Close
      'Close Excel
      'xlApp.Quit
      MsgBox "done"
End Sub

Sub Build_Matrices()
    'Builds the [A] and {B} Matrices of the linear system [A]*{x}={B}
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
'Assigning values (force and moment potentials and applied force and
moment from excel file "Equilibrium_coefficient.xls"
'Matrix_A dimensions are set to max 19x19
'Under "Project", "References", include Microsoft Excel 9.0 Object Library
to call excel applications


Dim n, Temp_variable(1 To 5) As Integer 'To assist in assigning the
variable to the matrix for fingers, for indexing purpose

Set xlApp = CreateObject("Excel.Application")
Set xlBook =
Workbooks.Open(FileName:="C:\Sung\PhD\Biomechanical_VBProgram\
MStress_Muscle-Tendons\Equilibrium_coefficient.xls")
'Set xlSheet = xlBook.Sheets.Add

  n = 0

  If Combo1.Text = "Thumb" Then
    'Assign values for tendons variables (Matrix A)
    For i = 1 To 18
      For j = 1 To 5  'because FPB=OPP, don't need #6 for OPP
        Matrix_Thumb(i, j) = xlBook.Sheets("Thumb").Cells(i + 1, j +
2).Value


      Next j
    Next i

    'Assign values for compressive and constraint forces and constraint
moment (13 variables) of Matrix_Thumb
    For i = 1 To 18
      For j = 6 To 18
        Matrix_Thumb(i, j) = xlBook.Sheets("Thumb").Cells(i + 1, j +
4).Value

      Next j
    Next i

    'Assign values for constants (Array B)
    For i = 1 To 18
      Array_Thumb(i) = xlBook.Sheets("Thumb").Cells(i + 1, 24).Value

    Next i
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
   ElseIf Combo1.Text = "IndexFinger" Then
      'Assign values for tendons variables (4 out of 9 were assumed to be 0)
for 126 combinations of Matrix_Finger
      '(Matrix A)
      For var1 = 1 To 5
         Temp_variable(1) = var1

         For var2 = var1 + 1 To 6
            Temp_variable(2) = var2

            For var3 = var2 + 1 To 7
               Temp_variable(3) = var3

               For var4 = var3 + 1 To 8
                  Temp_variable(4) = var4

                  For var5 = var4 + 1 To 9
                     Temp_variable(5) = var5
                     n = n + 1 'counting 126 total combinations

                     'Assigning matrix values for each combination for
tendons' variables
                     For i = 1 To 19
                        For j = 1 To 5
                           Matrix_Finger(n, i, j) = xlBook.Sheets("IF").Cells(i
+ 1, Temp_variable(j) + 2).Value

                        Next j
                     Next i

                  Next var5
               Next var4
            Next var3
         Next var2
      Next var1

      'Assign values for compressive and constraint forces and constraint
moment (14 variables, same for all 126 combinations) of Matrix_Finger
      For i = 1 To 126
         For j = 1 To 19
            For k = 6 To 19
               Matrix_Finger(i, j, k) = xlBook.Sheets("IF").Cells(j + 1, k +
8).Value
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
        Next k
      Next j
    Next i

    'Assign values for constants (Array B)
    For i = 1 To 19
      Array_Finger(i) = xlBook.Sheets("IF").Cells(i + 1, 29).Value

    Next i


  ElseIf Combo1.Text = "MiddleFinger" Then
    'Assign values for tendons variables (4 of 9 were assumed to be 0) for
126 combinations of Matrix_Finger
    '(Matrix A)

    For var1 = 1 To 5
      Temp_variable(1) = var1

      For var2 = var1 + 1 To 6
        Temp_variable(2) = var2

        For var3 = var2 + 1 To 7
          Temp_variable(3) = var3

          For var4 = var3 + 1 To 8
            Temp_variable(4) = var4

            For var5 = var4 + 1 To 9
              Temp_variable(5) = var5
              n = n + 1 'counting 126 total combinations

              'Assigning matrix values for each combination for
tendons' variables
              For i = 1 To 19
                For j = 1 To 5
                  Matrix_Finger(n, i, j) = xlBook.Sheets("MF").Cells(i
+ 1, Temp_variable(j) + 2).Value

                Next j
              Next i
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
            Next var5
          Next var4
        Next var3
      Next var2
    Next var1

    'Assign values for compressive and constraint forces and constraint
moment (14 variables, same for all 126 combinations) of Matrix_Finger
    For i = 1 To 126
      For j = 1 To 19
        For k = 6 To 19
          Matrix_Finger(i, j, k) = xlBook.Sheets("MF").Cells(j + 1, k +
8).Value

        Next k
      Next j
    Next i

    'Assign values for constants (Array B)
    For i = 1 To 19
      Array_Finger(i) = xlBook.Sheets("MF").Cells(i + 1, 29).Value

    Next i


  ElseIf Combo1.Text = "RingFinger" Then
    'Assign values for tendons variables (4 of 9 were assumed to be 0) for
126 combinations of Matrix_Finger
    '(Matrix A)

    For var1 = 1 To 5
      Temp_variable(1) = var1

      For var2 = var1 + 1 To 6
        Temp_variable(2) = var2

        For var3 = var2 + 1 To 7
          Temp_variable(3) = var3

          For var4 = var3 + 1 To 8
            Temp_variable(4) = var4

            For var5 = var4 + 1 To 9
              Temp_variable(5) = var5
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
              n = n + 1 'counting 126 total combinations

              'Assigning matrix values for each combination for
tendons' variables
              For i = 1 To 19
                For j = 1 To 5
                  Matrix_Finger(n, i, j) = xlBook.Sheets("RF").Cells(i
+ 1, Temp_variable(j) + 2).Value

                Next j
              Next i

            Next var5
          Next var4
        Next var3
      Next var2
    Next var1

    'Assign values for compressive and constraint forces and constraint
moment (14 variables, same for all 126 combinations) of Matrix_Finger
    For i = 1 To 126
      For j = 1 To 19
        For k = 6 To 19
          Matrix_Finger(i, j, k) = xlBook.Sheets("RF").Cells(j + 1, k +
8).Value

        Next k
      Next j
    Next i

    'Assign values for constants (Array B)
    For i = 1 To 19
      Array_Finger(i) = xlBook.Sheets("RF").Cells(i + 1, 29).Value

    Next i


  ElseIf Combo1.Text = "LittleFinger" Then
    'Assign values for tendons variables (4 of 9 were assumed to be 0) for
126 combinations of Matrix_Finger
    '(Matrix A)

    For var1 = 1 To 5
      Temp_variable(1) = var1
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
            For var2 = var1 + 1 To 6
                Temp_variable(2) = var2

                For var3 = var2 + 1 To 7
                    Temp_variable(3) = var3

                    For var4 = var3 + 1 To 8
                        Temp_variable(4) = var4

                        For var5 = var4 + 1 To 9
                            Temp_variable(5) = var5
                            n = n + 1 'counting 126 total combinations

                            'Assigning matrix values for each combination for
tendons' variables
                            For i = 1 To 19
                                For j = 1 To 5
                                    Matrix_Finger(n, i, j) = xlBook.Sheets("LF").Cells(i
+ 1, Temp_variable(j) + 2).Value

                                Next j
                            Next i

                        Next var5
                    Next var4
                Next var3
            Next var2
        Next var1

        'Assign values for compressive and constraint forces and constraint
moment (14 variables, same for all 126 combinations) of Matrix_Finger
        For i = 1 To 126
            For j = 1 To 19
                For k = 6 To 19
                    Matrix_Finger(i, j, k) = xlBook.Sheets("LF").Cells(j + 1, k +
8).Value

                Next k
            Next j
        Next i


        'Assign values for constants (Array B)
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
        For i = 1 To 19
          Array_Finger(i) = xlBook.Sheets("LF").Cells(i + 1, 29).Value

        Next i

      End If

End Sub

Sub Build_Triangular_Matrix_Thumb()
    'Uses Gauss elimination method in order to build a triangular matrix from
    the matrix [A]
    'Triangularized Matrix Triangular_A is (System_DIM X System_DIM+1)
    because it also includes
    'the array {b} with the constants:
    '[ a11 a12 a13 | b1 ]
    '[ a21 a22 a23 | b2 ]
    '[ a31 a32 a33 | b3 ] etc

    On Error GoTo errhandler_thumb 'In case the system cannot be solved
    (Determinant = 0)

    Solution_Problem_Thumb = False

    'Assign values from Matrix_Thumb (Matrix A)
    For n = 1 To 18
      For m = 1 To 18
        Triangular_Thumb(m, n) = Matrix_Thumb(m, n)

      Next m
    Next n

    'Assign values from Array_Thumb (Array b)
    For n = 1 To 18
      Triangular_Thumb(n, 19) = Array_Thumb(n)
    Next n

    'Triangularize the matrix
    For k = 1 To 17
      'Bring a non-zero element first by changes lines if necessary
      If Triangular_Thumb(k, k) = 0 Then
        For n = k To 18
          If Triangular_Thumb(n, k) <> 0 Then line_1 = n: Exit For 'Finds
    line_1 with non-zero element
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                Next n

                'Change line k with line_1
                For m = 1 To 19
                    temporary_1 = Triangular_Thumb(k, m)
                    Triangular_Thumb(k, m) = Triangular_Thumb(line_1, m)
                    Triangular_Thumb(line_1, m) = temporary_1
                Next m
            End If

            'For other lines, make a zero element by using:
            'Ai1=Aij-A11*(Aij/A11)
            'and change all the line using the same formula for other elements
            For n = k + 1 To 18
                If Triangular_Thumb(n, k) <> 0 Then 'if it is zero, stays as it is
                    multiplier_1 = Triangular_Thumb(n, k) / Triangular_Thumb(k, k)
                    For m = k To 19
                        Triangular_Thumb(n, m) = Triangular_Thumb(n, m) -
        Triangular_Thumb(k, m) * multiplier_1
                    Next m
                End If
            Next n
        Next k

        Exit Sub


        errhandler_thumb:

        Message$ = "An error occured during the solution process. Make sure that
        the system is stable and can be solved."
        response = MsgBox(Message$, vbCritical)
        Solution_Problem_Thumb = True

    End Sub



    Sub Build_Triangular_Matrix_Finger()
        'Uses Gauss elimination method in order to build a triangular matrix from
        the matrix [A]
        'Triangularized Matrix Triangular_A is (System_DIM X System_DIM+1)
        because it also includes
        'the array {b} with the constants:
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
'[ a11 a12 a13 | b1 ]
'[ a21 a22 a23 | b2 ]
'[ a31 a32 a33 | b3 ] etc

On Error GoTo errhandler_finger 'In case the system cannot be solved
(Determinant = 0)

Solution_Problem_Finger(Solution_Problem_index) = False

'Assign values from Matrix_Finger (Matrix A)
For n = 1 To 19
   For m = 1 To 19
      Triangular_Finger(Solution_Problem_index, m, n) =
Matrix_Finger(Solution_Problem_index, m, n)

   Next m
Next n

'Assign values from Array_Thumb (Array b)
For n = 1 To 19
   Triangular_Finger(Solution_Problem_index, n, 20) = Array_Finger(n)
Next n

'Triangularize the matrix
For k = 1 To 18
   'Bring a non-zero element first by changes lines if necessary
   If Triangular_Finger(Solution_Problem_index, k, k) = 0 Then
      For n = k To 19
         If Triangular_Finger(Solution_Problem_index, n, k) <> 0 Then
line_1 = n: Exit For 'Finds line_1 with non-zero element
      Next n

      'Change line k with line_1
      For m = 1 To 20
         temporary_1 = Triangular_Finger(Solution_Problem_index, k, m)
         Triangular_Finger(Solution_Problem_index, k, m) =
Triangular_Finger(Solution_Problem_index, line_1, m)
         Triangular_Finger(Solution_Problem_index, line_1, m) =
temporary_1
      Next m
   End If

   'For other lines, make a zero element by using:
   'Ai1=Aij-A11*(Aij/A11)
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
       'and change all the line using the same formula for other elements
       For n = k + 1 To 19
          If Triangular_Finger(Solution_Problem_index, n, k) <> 0 Then 'if it is
    zero, stays as it is
             multiplier_1 = Triangular_Finger(Solution_Problem_index, n, k) /
    Triangular_Finger(Solution_Problem_index, k, k)
             For m = k To 20
                Triangular_Finger(Solution_Problem_index, n, m) =
    Triangular_Finger(Solution_Problem_index, n, m) -
    (Triangular_Finger(Solution_Problem_index, k, m) * multiplier_1)
             Next m
          End If
       Next n
    Next k


    Exit Sub


    errhandler_finger:

    Solution_Problem_Finger(Solution_Problem_index) = True

End Sub

Sub Back_Substitution_Thumb()
    'Calculates the Solution array {x} of thumb using back substitution

    Division_Tri_Matrix_Thumb = True
    If Triangular_Thumb(18, 18) <> 0 Then
       'First, calculate last Xi (for i = System_DIM)
       Solution_Thumb(18) = Triangular_Thumb(18, 19) /
    Triangular_Thumb(18, 18)

       'Back substitution for the other Xi:
       For n = 1 To 17
          sum_1 = 0
          For m = 1 To n
             sum_1 = sum_1 + Solution_Thumb(19 - m) *
    Triangular_Thumb(18 - n, 19 - m)
          Next m
          Solution_Thumb(18 - n) = (Triangular_Thumb(18 - n, 19) - sum_1) /
    Triangular_Thumb(18 - n, 18 - n)
       Next n
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
    Else
      Division_Tri_Matrix_Thumb = False
    End If

    'Calculate Determinant of matrix [A] of thumb
    'It is the product of the diagonal elements of the triangular matrix
    'not necessary now

    'Determinant_1 = 1 'Initialize the product
    'For n = 1 To 18
      'Determinant_1 = Determinant_1 * Triangular_Thumb(n, n)
    'Next n

End Sub

Sub Back_Substitution_Finger()
    'Calculates the Solution array {x} using back substitution

    Division_Tri_Matrix_Finger(Solution_Problem_index) = True 'Set to true
    first

    'If one of the diagnal cell is 0, can not solve the problem
    For i = 1 To 19
      If Triangular_Finger(Solution_Problem_index, i, i) = 0 Then
        Division_Tri_Matrix_Finger(Solution_Problem_index) = False
      End If
    Next i


    If Division_Tri_Matrix_Finger(Solution_Problem_index) = True Then
      'First, calculate last Xi (for i = System_DIM)
      Solution_Finger(Solution_Problem_index, 19) =
    Triangular_Finger(Solution_Problem_index, 19, 20) /
    Triangular_Finger(Solution_Problem_index, 19, 19)

      'Back substitution for the other Xi:
      For n = 1 To 18
        sum_1 = 0
        For m = 1 To n
          sum_1 = sum_1 + Solution_Finger(Solution_Problem_index, 20 -
    m) * Triangular_Finger(Solution_Problem_index, 19 - n, 20 - m)
        Next m
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
        Solution_Finger(Solution_Problem_index, 19 - n) =
    (Triangular_Finger(Solution_Problem_index, 19 - n, 20) - sum_1) /
    Triangular_Finger(Solution_Problem_index, 19 - n, 19 - n)

      Next n

    Else

      Solution_Problem_Finger(Solution_Problem_index) = True
    End If
    'Calculate Determinant of matrix [A]
    'It is the product of the diagonal elements of the triangular matrix
    'not necessary now, should have an array to store all 126 possible
    determinant

    'Determinant_1 = 1 'Initialize the product
    'For n = 1 To 19
      'Determinant_1 = Determinant_1 *
    Triangular_Finger(Solution_Problem_index, n, n)
    'Next n

End Sub

Sub Validity_Check_Finger()
    'Check if the solution is valid according to the journal and output the
    solution to excel workbook

    Dim Constraints(1 To 3) As Boolean 'Should meet all three constraints to
    be valid solutions

    For i = 1 To 3
      Constraints(i) = True 'set all three to true first
    Next i

    If Solution_Problem_Finger(Solution_Problem_index) = False Then

      '1st Constraint: Tendons force (X1~X5) >= 0, Chao et al. (1976) p392
      For i = 1 To 5
        If Solution_Finger(Solution_Problem_index, i) < 0 Then
          Constraints(1) = False
        End If
      Next i
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
      '2nd Constraint: Axial Compression CX (X6, X11, X16) > = 0, Chao et
    al. (1976) p392 and An et al. (1979) p 784
      'For i = 1 To 3
        'If Solution_Finger(Solution_Problem_index, i * 5 + 1) < 0 Then
          'Constraints(2) = False
        'End If
      'Next i

      'If did not meet any one of the three constraints, then, the solution is not
    valid
      If Constraints(1) = True And Constraints(2) = True And Constraints(3) =
    True Then
        Solution_Validity_Finger(Solution_Problem_index) = True
      End If


    End If

End Sub

Sub Solutions_Excel_Thumb()
    'Output valid solution of thumb to excel workbook
    'No other limitations (no need validity check) except assumptions A and B
    in the paper

    Set xlApp = CreateObject("Excel.Application")
      xlApp.Visible = True
      xlApp.Workbooks.Add

      For i = 1 To 18
        'Show the solutions of all 18 variables in first row
        xlApp.Sheets("sheet1").Cells(1, i).Value = Solution_Thumb(i)
      Next i

End Sub

Sub Solutions_Excel_Finger()
    'Output valid solutions of fingers to excel workbook

    Dim n, m, Temp_variable(1 To 5) As Integer 'To assist recover the 9
    tendons variables corresponding to X1 ~ X5

    Set xlApp = CreateObject("Excel.Application")
      xlApp.Visible = True
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
   xlApp.Workbooks.Add

n = 0
m = 0

For var1 = 1 To 5
   Temp_variable(1) = var1

   For var2 = var1 + 1 To 6
      Temp_variable(2) = var2

      For var3 = var2 + 1 To 7
         Temp_variable(3) = var3

         For var4 = var3 + 1 To 8
            Temp_variable(4) = var4

            For var5 = var4 + 1 To 9
               Temp_variable(5) = var5

               n = n + 1

               If Solution_Validity_Finger(n) = True Then
                  'Output valid solutions to excel

                  m = m + 1

                  'Assigning tendon variables solutions
                  For i = 1 To 5
                     xlApp.Sheets("sheet1").Cells(m, Temp_variable(i)).Value
= Solution_Finger(n, i)
                  Next i

                  'Assigning 0 to the remaining 4 tendon variables
                  For j = 1 To 9
                     If j <> Temp_variable(1) And j <> Temp_variable(2) And
j <> Temp_variable(3) And j <> Temp_variable(4) And j <>
Temp_variable(5) Then
                        xlApp.Sheets("sheet1").Cells(m, j).Value = 0
                     End If
                  Next j

                  'Assigning constraint forces and moments solutions
                  For k = 6 To 19
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                  'Show the solutions of all 14 variables to m row
                  xlApp.Sheets("sheet1").Cells(m, k + 4).Value =
    Solution_Finger(n, k)

                Next k
              End If

            Next var5
          Next var4
        Next var3
      Next var2
    Next var1

End Sub
```

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 5 Contact Forces (in Newton) at Tip of Thumb and 2nd Phalanx of the Index Finger Measured for Roller Task Simulations for Ten Female Subjects

| | | | | Tip of Th | | | 2nd Ph of IF | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | Median | Min | Max | Median | Min | Max |
| 1 | --- | --- | 10 | 6.8 | 4.2 | 13.3 | 5.5 | 2.7 | 14.2 |
| 1 | --- | --- | 20 | 9.1 | 4.9 | 15.4 | 12.3 | 3.1 | 22.9 |
| 1 | --- | --- | 30 | 12.6 | 6.1 | 20.4 | 16.5 | 2.9 | 29.1 |
| 2 | 1 | 1 | 10 | 6.2 | 3.3 | 18.8 | 8.0 | 1.9 | 17.6 |
| 2 | 1 | 1 | 20 | 8.9 | 6.2 | 31.9 | 11.3 | 3.5 | 30.4 |
| 2 | 1 | 1 | 30 | 19.6 | 6.8 | 45.6 | 14.3 | 4.8 | 41.6 |
| 2 | 1 | 2 | 10 | 7.0 | 4.0 | 20.5 | 9.5 | 2.2 | 21.2 |
| 2 | 1 | 2 | 20 | 9.9 | 3.3 | 20.3 | 15.7 | 4.8 | 31.0 |
| 2 | 1 | 2 | 30 | 20.3 | 6.6 | 32.0 | 19.0 | 8.2 | 34.6 |
| 2 | 1 | 3 | 10 | 6.0 | 3.1 | 17.0 | 11.2 | 2.2 | 26.7 |
| 2 | 1 | 3 | 20 | 9.3 | 4.6 | 23.0 | 18.2 | 4.5 | 28.6 |
| 2 | 1 | 3 | 30 | 17.5 | 4.6 | 27.6 | 18.5 | 6.3 | 29.7 |
| 2 | 2 | 1 | 10 | 7.8 | 3.3 | 23.2 | 8.9 | 3.0 | 18.0 |
| 2 | 2 | 1 | 20 | 10.5 | 9.0 | 25.9 | 15.2 | 8.0 | 25.1 |
| 2 | 2 | 1 | 30 | 15.4 | 11.7 | 30.3 | 17.4 | 9.2 | 36.3 |
| 2 | 2 | 2 | 10 | 7.2 | 3.3 | 19.3 | 8.6 | 2.9 | 18.1 |
| 2 | 2 | 2 | 20 | 12.0 | 7.3 | 24.5 | 12.8 | 7.6 | 23.9 |
| 2 | 2 | 2 | 30 | 14.7 | 8.6 | 37.4 | 17.8 | 8.9 | 28.4 |
| 2 | 2 | 3 | 10 | 6.2 | 3.0 | 21.1 | 10.5 | 2.7 | 19.4 |
| 2 | 2 | 3 | 20 | 9.7 | 7.4 | 28.6 | 11.9 | 2.2 | 29.2 |
| 2 | 2 | 3 | 30 | 15.6 | 7.1 | 29.0 | 15.1 | 7.1 | 28.6 |
| 3 | 1 | 1 | 10 | 8.4 | 3.1 | 19.1 | 10.5 | 2.8 | 21.1 |
| 3 | 1 | 1 | 20 | 12.9 | 6.1 | 25.5 | 16.0 | 4.9 | 26.2 |
| 3 | 1 | 1 | 30 | 17.6 | 10.6 | 26.0 | 20.0 | 7.4 | 35.3 |
| 3 | 1 | 2 | 10 | 8.5 | 2.9 | 14.3 | 10.5 | 3.6 | 17.6 |
| 3 | 1 | 2 | 20 | 14.4 | 8.4 | 23.0 | 15.7 | 3.4 | 26.9 |
| 3 | 1 | 2 | 30 | 17.3 | 11.3 | 25.6 | 21.2 | 7.7 | 34.1 |
| 3 | 1 | 3 | 10 | 8.2 | 3.5 | 13.8 | 8.3 | 3.3 | 19.3 |
| 3 | 1 | 3 | 20 | 12.1 | 6.7 | 18.4 | 13.1 | 6.4 | 20.2 |
| 3 | 1 | 3 | 30 | 18.3 | 10.9 | 26.0 | 18.9 | 7.0 | 28.3 |
| 3 | 2 | 1 | 10 | 7.9 | 2.6 | 17.6 | 9.8 | 3.7 | 19.1 |
| 3 | 2 | 1 | 20 | 13.5 | 3.8 | 27.0 | 15.2 | 6.4 | 24.4 |
| 3 | 2 | 1 | 30 | 17.6 | 12.4 | 30.1 | 16.7 | 5.6 | 34.9 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 5 Contact Forces (in Newton) at Tip of Thumb and 2nd Phalanx of the Index Finger Measured for Roller Task Simulations for Ten Female Subjects (Continued)

| | | | | Tip of Th | | | 2nd Ph of IF | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | Median | Min | Max | Median | Min | Max |
| 3 | 2 | 2 | 10 | 9.6 | 1.9 | 24.9 | 9.8 | 4.4 | 17.0 |
| 3 | 2 | 2 | 20 | 15.4 | 4.6 | 36.9 | 13.5 | 3.9 | 25.9 |
| 3 | 2 | 2 | 30 | 19.3 | 9.9 | 39.8 | 20.2 | 4.0 | 41.5 |
| 3 | 2 | 3 | 10 | 7.2 | 1.8 | 20.2 | 8.4 | 3.2 | 13.2 |
| 3 | 2 | 3 | 20 | 13.0 | 3.1 | 31.4 | 11.3 | 4.6 | 25.9 |
| 3 | 2 | 3 | 30 | 18.1 | 10.2 | 41.0 | 17.5 | 3.9 | 42.9 |
| 4 | 1 | 1 | 10 | 8.6 | 3.2 | 16.3 | 9.8 | 3.3 | 21.3 |
| 4 | 1 | 1 | 20 | 12.8 | 7.3 | 22.8 | 10.4 | 6.6 | 23.3 |
| 4 | 1 | 1 | 30 | 15.7 | 12.2 | 20.7 | 18.1 | 12.0 | 37.1 |
| 4 | 1 | 2 | 10 | 7.8 | 1.4 | 24.8 | 11.3 | 3.2 | 15.7 |
| 4 | 1 | 2 | 20 | 14.4 | 8.5 | 22.9 | 12.8 | 6.7 | 29.6 |
| 4 | 1 | 2 | 30 | 17.3 | 11.4 | 43.1 | 22.6 | 9.2 | 32.6 |
| 4 | 1 | 3 | 10 | 8.1 | 2.7 | 20.9 | 7.6 | 2.9 | 18.9 |
| 4 | 1 | 3 | 20 | 11.4 | 5.6 | 23.8 | 11.1 | 6.3 | 19.6 |
| 4 | 1 | 3 | 30 | 14.7 | 8.6 | 31.8 | 15.1 | 7.4 | 33.0 |
| 4 | 2 | 1 | 10 | 8.0 | 2.9 | 16.9 | 12.0 | 4.3 | 13.9 |
| 4 | 2 | 1 | 20 | 11.9 | 7.3 | 21.6 | 13.6 | 4.7 | 34.2 |
| 4 | 2 | 1 | 30 | 14.0 | 5.3 | 28.6 | 17.2 | 2.2 | 38.7 |
| 4 | 2 | 2 | 10 | 7.5 | 3.5 | 18.7 | 10.5 | 4.7 | 16.0 |
| 4 | 2 | 2 | 20 | 11.5 | 6.3 | 18.6 | 14.1 | 4.5 | 32.0 |
| 4 | 2 | 2 | 30 | 18.0 | 8.1 | 27.5 | 17.9 | 3.1 | 43.7 |
| 4 | 2 | 3 | 10 | 7.2 | 1.9 | 17.8 | 7.9 | 3.4 | 26.0 |
| 4 | 2 | 3 | 20 | 11.4 | 5.0 | 24.5 | 12.9 | 5.8 | 30.2 |
| 4 | 2 | 3 | 30 | 12.4 | 5.8 | 27.6 | 15.3 | 7.3 | 28.8 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 5 Contact Forces (in Newton) at Tips of the Middle and Ring Fingers Measured for Roller Task Simulations for Ten Female Subjects (Continued)

|  |  |  |  | Tip of MF |  |  | Tip of RF |  |  |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | Median | Min | Max | Median | Min | Max |
| 1 | --- | --- | 10 | 3.2 | 1.8 | 6.4 | 3.7 | 1.5 | 5.6 |
| 1 | --- | --- | 20 | 4.1 | 2.6 | 9.0 | 7.8 | 1.6 | 10.8 |
| 1 | --- | --- | 30 | 5.4 | 2.0 | 15.0 | 11.0 | 1.9 | 18.4 |
| 2 | 1 | 1 | 10 | 3.9 | 2.4 | 8.2 | 3.1 | 1.6 | 6.3 |
| 2 | 1 | 1 | 20 | 5.6 | 2.1 | 8.9 | 5.0 | 1.8 | 11.0 |
| 2 | 1 | 1 | 30 | 5.8 | 2.8 | 14.3 | 5.6 | 1.5 | 21.6 |
| 2 | 1 | 2 | 10 | 3.7 | 1.7 | 10.4 | 3.6 | 1.4 | 6.6 |
| 2 | 1 | 2 | 20 | 6.2 | 1.9 | 12.4 | 6.4 | 1.5 | 13.1 |
| 2 | 1 | 2 | 30 | 5.9 | 2.4 | 14.1 | 7.8 | 1.8 | 21.2 |
| 2 | 1 | 3 | 10 | 2.9 | 1.6 | 5.6 | 3.2 | 1.5 | 4.0 |
| 2 | 1 | 3 | 20 | 4.3 | 1.6 | 11.4 | 4.3 | 1.0 | 13.5 |
| 2 | 1 | 3 | 30 | 6.3 | 3.0 | 12.5 | 7.9 | 1.8 | 16.2 |
| 2 | 2 | 1 | 10 | 3.3 | 1.3 | 9.9 | 3.0 | 0.9 | 10.6 |
| 2 | 2 | 1 | 20 | 4.7 | 1.3 | 13.3 | 4.2 | 1.0 | 7.7 |
| 2 | 2 | 1 | 30 | 6.8 | 1.4 | 16.3 | 7.0 | 1.1 | 13.0 |
| 2 | 2 | 2 | 10 | 3.9 | 1.2 | 15.4 | 3.2 | 1.0 | 7.3 |
| 2 | 2 | 2 | 20 | 4.7 | 1.2 | 17.6 | 4.8 | 1.0 | 9.7 |
| 2 | 2 | 2 | 30 | 6.0 | 2.0 | 13.7 | 10.2 | 1.6 | 20.4 |
| 2 | 2 | 3 | 10 | 3.6 | 1.3 | 12.9 | 3.7 | 1.0 | 5.8 |
| 2 | 2 | 3 | 20 | 4.7 | 1.4 | 13.7 | 4.3 | 1.1 | 11.4 |
| 2 | 2 | 3 | 30 | 4.9 | 1.3 | 15.7 | 7.4 | 1.4 | 16.5 |
| 3 | 1 | 1 | 10 | 3.2 | 1.2 | 6.1 | 2.5 | 1.2 | 5.5 |
| 3 | 1 | 1 | 20 | 5.8 | 1.6 | 9.0 | 3.9 | 1.5 | 6.5 |
| 3 | 1 | 1 | 30 | 6.5 | 1.7 | 19.7 | 6.0 | 1.9 | 11.9 |
| 3 | 1 | 2 | 10 | 3.7 | 1.5 | 12.3 | 2.4 | 1.4 | 5.3 |
| 3 | 1 | 2 | 20 | 5.4 | 1.5 | 8.7 | 4.8 | 1.4 | 7.5 |
| 3 | 1 | 2 | 30 | 5.8 | 2.0 | 20.1 | 6.2 | 1.7 | 13.2 |
| 3 | 1 | 3 | 10 | 3.2 | 1.7 | 7.7 | 2.8 | 1.4 | 5.5 |
| 3 | 1 | 3 | 20 | 4.4 | 1.5 | 11.4 | 4.1 | 1.5 | 5.6 |
| 3 | 1 | 3 | 30 | 4.2 | 1.6 | 15.9 | 5.7 | 1.8 | 8.8 |
| 3 | 2 | 1 | 10 | 3.2 | 1.2 | 9.6 | 3.4 | 1.2 | 8.0 |
| 3 | 2 | 1 | 20 | 4.0 | 1.2 | 9.2 | 4.2 | 1.2 | 9.8 |
| 3 | 2 | 1 | 30 | 5.6 | 1.1 | 11.8 | 6.1 | 1.2 | 14.3 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 5 Contact Forces (in Newton) at Tips of the Middle and Ring Fingers Measured for Roller Task Simulations for Ten Female Subjects (Continued)

| | | | | Tip of MF | | | Tip of RF | | |
|---|---|---|---|---|---|---|---|---|---|
| **Glove** | **Th** | **Layer** | **TF** | **Median** | **Min** | **Max** | **Median** | **Min** | **Max** |
| 3 | 2 | 2 | 10 | 3.2 | 1.3 | 6.6 | 3.1 | 1.2 | 9.0 |
| 3 | 2 | 2 | 20 | 3.5 | 1.1 | 10.0 | 4.8 | 1.3 | 8.0 |
| 3 | 2 | 2 | 30 | 5.5 | 1.2 | 16.7 | 7.7 | 1.5 | 13.7 |
| 3 | 2 | 3 | 10 | 4.6 | 1.2 | 15.7 | 4.0 | 1.4 | 9.8 |
| 3 | 2 | 3 | 20 | 3.8 | 1.4 | 8.0 | 4.7 | 1.3 | 7.4 |
| 3 | 2 | 3 | 30 | 4.8 | 1.6 | 12.4 | 7.4 | 1.3 | 10.7 |
| 4 | 1 | 1 | 10 | 3.0 | 1.3 | 9.0 | 4.0 | 1.7 | 7.5 |
| 4 | 1 | 1 | 20 | 4.7 | 1.7 | 7.4 | 5.4 | 2.0 | 9.4 |
| 4 | 1 | 1 | 30 | 3.7 | 1.2 | 13.1 | 7.1 | 2.0 | 14.0 |
| 4 | 1 | 2 | 10 | 3.8 | 1.6 | 11.6 | 4.5 | 1.4 | 14.9 |
| 4 | 1 | 2 | 20 | 3.9 | 1.7 | 9.2 | 6.1 | 1.7 | 12.1 |
| 4 | 1 | 2 | 30 | 4.8 | 2.1 | 14.5 | 7.8 | 1.5 | 21.9 |
| 4 | 1 | 3 | 10 | 3.2 | 1.4 | 8.2 | 5.0 | 1.5 | 9.2 |
| 4 | 1 | 3 | 20 | 4.0 | 1.5 | 12.1 | 5.9 | 1.3 | 13.3 |
| 4 | 1 | 3 | 30 | 5.1 | 1.8 | 16.9 | 8.9 | 1.9 | 15.9 |
| 4 | 2 | 1 | 10 | 4.7 | 1.9 | 12.4 | 3.5 | 1.2 | 9.5 |
| 4 | 2 | 1 | 20 | 6.8 | 1.8 | 8.8 | 5.6 | 1.2 | 11.5 |
| 4 | 2 | 1 | 30 | 9.2 | 1.8 | 13.4 | 7.0 | 1.1 | 28.2 |
| 4 | 2 | 2 | 10 | 5.0 | 2.1 | 14.3 | 4.6 | 1.2 | 20.7 |
| 4 | 2 | 2 | 20 | 7.0 | 1.8 | 12.5 | 5.0 | 1.4 | 17.2 |
| 4 | 2 | 2 | 30 | 9.6 | 2.3 | 14.3 | 9.5 | 1.1 | 26.5 |
| 4 | 2 | 3 | 10 | 4.9 | 2.6 | 8.7 | 4.6 | 1.2 | 11.8 |
| 4 | 2 | 3 | 20 | 5.5 | 2.2 | 11.2 | 6.5 | 1.1 | 11.7 |
| 4 | 2 | 3 | 30 | 8.0 | 2.7 | 12.5 | 9.8 | 1.2 | 30.0 |

| | |
|---|---|
| Glove | 1: bare hand; 2: butyl; 3: hypalon; 4: neoprene |
| Th (Thickness) | 1: 0.015"; 2: 0.03" |
| Layer | 1: single layer; 2: double layer; 3: triple layer |
| TF (Target Force) | Task demands in Newton |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 6 Contact Forces (in Newton) Measured for Tweezers Task Simulations for Eleven Female Subjects

| | | | | Tip of Thumb | | | Tip of IF | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | Median | Min | Max | Median | Min | Max |
| 1 | --- | --- | 5 | 4.9 | 2.1 | 17.1 | 4.6 | 3.7 | 7.9 |
| 1 | --- | --- | 10 | 10.2 | 3.4 | 29.8 | 8.5 | 6.0 | 14.2 |
| 1 | --- | --- | 15 | 12.4 | 4.9 | 44.7 | 14.9 | 7.2 | 23.1 |
| 2 | 1 | 1 | 5 | 5.9 | 4.1 | 20.8 | 5.5 | 4.3 | 10.0 |
| 2 | 1 | 1 | 10 | 15.4 | 8.0 | 37.3 | 12.2 | 7.7 | 17.9 |
| 2 | 1 | 1 | 15 | 25.7 | 13.9 | 55.4 | 20.6 | 12.5 | 27.3 |
| 2 | 1 | 2 | 5 | 6.3 | 4.1 | 19.6 | 5.3 | 3.9 | 9.6 |
| 2 | 1 | 2 | 10 | 14.3 | 9.5 | 33.4 | 10.8 | 6.5 | 20.5 |
| 2 | 1 | 2 | 15 | 20.3 | 13.8 | 46.9 | 17.9 | 12.4 | 29.9 |
| 2 | 1 | 3 | 5 | 5.6 | 3.6 | 18.0 | 5.7 | 4.3 | 9.5 |
| 2 | 1 | 3 | 10 | 11.9 | 6.2 | 32.4 | 11.2 | 5.0 | 17.9 |
| 2 | 1 | 3 | 15 | 18.7 | 11.7 | 49.5 | 17.8 | 9.8 | 33.1 |
| 2 | 2 | 1 | 5 | 6.2 | 4.1 | 16.6 | 6.5 | 4.7 | 8.7 |
| 2 | 2 | 1 | 10 | 12.7 | 8.1 | 33.4 | 14.5 | 7.1 | 20.6 |
| 2 | 2 | 1 | 15 | 19.5 | 14.6 | 56.8 | 24.0 | 8.2 | 31.7 |
| 2 | 2 | 2 | 5 | 5.6 | 4.1 | 20.9 | 5.7 | 4.3 | 10.4 |
| 2 | 2 | 2 | 10 | 14.0 | 7.5 | 33.3 | 13.5 | 7.0 | 18.5 |
| 2 | 2 | 2 | 15 | 27.5 | 15.9 | 57.9 | 19.2 | 7.7 | 26.9 |
| 2 | 2 | 3 | 5 | 5.3 | 4.1 | 18.5 | 5.9 | 4.0 | 8.7 |
| 2 | 2 | 3 | 10 | 12.1 | 9.2 | 32.5 | 12.6 | 5.6 | 17.9 |
| 2 | 2 | 3 | 15 | 24.7 | 16.1 | 50.3 | 17.6 | 8.6 | 25.3 |
| 3 | 1 | 1 | 5 | 5.8 | 4.5 | 16.1 | 7.0 | 4.9 | 8.6 |
| 3 | 1 | 1 | 10 | 15.0 | 8.8 | 31.7 | 11.6 | 8.1 | 18.5 |
| 3 | 1 | 1 | 15 | 18.5 | 7.6 | 49.0 | 19.6 | 11.4 | 34.4 |
| 3 | 1 | 2 | 5 | 7.2 | 4.1 | 17.5 | 6.2 | 4.7 | 8.8 |
| 3 | 1 | 2 | 10 | 14.0 | 9.1 | 34.8 | 12.7 | 8.2 | 17.1 |
| 3 | 1 | 2 | 15 | 17.1 | 9.1 | 53.6 | 19.5 | 12.1 | 31.2 |
| 3 | 1 | 3 | 5 | 5.6 | 3.7 | 18.0 | 5.6 | 4.3 | 8.6 |
| 3 | 1 | 3 | 10 | 9.6 | 6.4 | 28.4 | 11.9 | 8.4 | 19.9 |
| 3 | 1 | 3 | 15 | 16.4 | 12.1 | 44.3 | 15.3 | 9.3 | 31.7 |
| 3 | 2 | 1 | 5 | 6.6 | 4.6 | 18.8 | 6.3 | 4.8 | 9.5 |
| 3 | 2 | 1 | 10 | 11.7 | 8.4 | 31.4 | 13.2 | 6.3 | 22.8 |
| 3 | 2 | 1 | 15 | 23.3 | 14.4 | 55.4 | 18.6 | 7.3 | 37.6 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 6 Contact Forces (in Newton) Measured for Tweezers Task Simulations for Eleven Female Subjects (Continued)

| | | | | Tip of Thumb | | | Tip of IF | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | Median | Min | Max | Median | Min | Max |
| 3 | 2 | 2 | 5 | 6.8 | 3.7 | 16.7 | 6.7 | 4.9 | 11.4 |
| 3 | 2 | 2 | 10 | 15.0 | 5.7 | 33.7 | 12.4 | 5.2 | 22.2 |
| 3 | 2 | 2 | 15 | 23.6 | 8.7 | 49.6 | 18.9 | 7.0 | 28.8 |
| 3 | 2 | 3 | 5 | 6.5 | 3.5 | 19.6 | 6.1 | 3.7 | 9.2 |
| 3 | 2 | 3 | 10 | 14.4 | 5.0 | 32.0 | 12.5 | 3.3 | 17.9 |
| 3 | 2 | 3 | 15 | 21.5 | 11.2 | 51.5 | 17.1 | 5.2 | 30.6 |
| 4 | 1 | 1 | 5 | 5.5 | 3.7 | 19.6 | 6.0 | 4.3 | 9.8 |
| 4 | 1 | 1 | 10 | 11.9 | 8.1 | 35.6 | 13.2 | 8.2 | 19.7 |
| 4 | 1 | 1 | 15 | 21.7 | 11.0 | 50.0 | 19.6 | 12.3 | 33.9 |
| 4 | 1 | 2 | 5 | 5.9 | 2.9 | 18.7 | 7.0 | 3.8 | 11.4 |
| 4 | 1 | 2 | 10 | 11.4 | 7.7 | 30.1 | 11.4 | 7.9 | 19.8 |
| 4 | 1 | 2 | 15 | 19.0 | 13.7 | 50.4 | 19.1 | 13.6 | 27.5 |
| 4 | 1 | 3 | 5 | 5.5 | 3.0 | 17.5 | 6.1 | 4.5 | 10.4 |
| 4 | 1 | 3 | 10 | 10.1 | 6.2 | 29.8 | 11.7 | 6.1 | 19.8 |
| 4 | 1 | 3 | 15 | 16.4 | 12.2 | 52.9 | 18.2 | 11.6 | 28.0 |
| 4 | 2 | 1 | 5 | 6.9 | 3.3 | 18.6 | 6.0 | 4.7 | 10.9 |
| 4 | 2 | 1 | 10 | 13.8 | 8.8 | 32.2 | 11.5 | 7.9 | 21.0 |
| 4 | 2 | 1 | 15 | 22.3 | 12.4 | 48.5 | 16.6 | 8.1 | 27.7 |
| 4 | 2 | 2 | 5 | 5.5 | 3.3 | 21.3 | 8.5 | 4.2 | 11.3 |
| 4 | 2 | 2 | 10 | 9.8 | 6.6 | 42.0 | 16.3 | 7.0 | 27.1 |
| 4 | 2 | 2 | 15 | 15.4 | 7.0 | 54.9 | 20.7 | 10.8 | 40.5 |
| 4 | 2 | 3 | 5 | 5.8 | 3.4 | 19.9 | 5.8 | 4.4 | 11.6 |
| 4 | 2 | 3 | 10 | 9.7 | 6.7 | 37.3 | 12.9 | 4.8 | 20.9 |
| 4 | 2 | 3 | 15 | 18.1 | 12.1 | 47.7 | 16.5 | 8.4 | 26.1 |

| | |
|---|---|
| Glove | 1: bare hand; 2: butyl; 3: hypalon; 4: neoprene |
| Th (Thickness) | 1: 0.015"; 2: 0.03" |
| Layer | 1: single layer; 2: double layer; 3: triple layer |
| TF (Target Force) | Task demands in Newton |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 7 Contact Forces (in Newton) at Tip of Thumb and 2nd Phalanx of Index Finger Measured for Wrench Task Simulations for Ten Female Subjects

| | | | | Tip of Thumb | | | 2nd Ph of IF | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TT | Median | Min | Max | Median | Min | Max |
| 1 | --- | --- | 10 | 4.5 | 3.4 | 12.2 | 3.8 | 2.3 | 11.8 |
| 1 | --- | --- | 40 | 6.5 | 2.9 | 15.1 | 7.3 | 2.7 | 28.2 |
| 1 | --- | --- | 80 | 7.2 | 4.5 | 20.6 | 9.2 | 3.6 | 46.9 |
| 2 | 1 | 1 | 10 | 6.3 | 1.7 | 12.4 | 4.1 | 2.3 | 10.2 |
| 2 | 1 | 1 | 40 | 7.8 | 2.3 | 23.5 | 7.5 | 3.4 | 19.2 |
| 2 | 1 | 1 | 80 | 13.5 | 2.8 | 36.0 | 9.8 | 6.1 | 24.2 |
| 2 | 1 | 2 | 10 | 5.9 | 1.8 | 19.8 | 3.8 | 2.3 | 11.1 |
| 2 | 1 | 2 | 40 | 6.5 | 3.0 | 18.3 | 7.5 | 3.5 | 13.6 |
| 2 | 1 | 2 | 80 | 14.0 | 2.7 | 31.9 | 8.2 | 3.4 | 22.5 |
| 2 | 1 | 3 | 10 | 5.0 | 2.5 | 15.7 | 3.7 | 3.0 | 13.6 |
| 2 | 1 | 3 | 40 | 11.2 | 2.3 | 19.0 | 7.9 | 3.3 | 15.2 |
| 2 | 1 | 3 | 80 | 15.8 | 2.3 | 23.2 | 9.6 | 5.1 | 18.1 |
| 2 | 2 | 1 | 10 | 5.6 | 1.0 | 10.4 | 3.7 | 2.5 | 9.3 |
| 2 | 2 | 1 | 40 | 12.2 | 3.4 | 24.0 | 8.2 | 3.9 | 16.8 |
| 2 | 2 | 1 | 80 | 13.1 | 3.8 | 26.0 | 8.6 | 4.4 | 31.0 |
| 2 | 2 | 2 | 10 | 5.4 | 1.3 | 13.9 | 4.8 | 1.9 | 13.3 |
| 2 | 2 | 2 | 40 | 8.1 | 3.2 | 18.1 | 6.3 | 4.1 | 18.1 |
| 2 | 2 | 2 | 80 | 10.0 | 3.7 | 25.4 | 10.1 | 3.7 | 26.9 |
| 2 | 2 | 3 | 10 | 4.7 | 1.1 | 11.4 | 4.9 | 2.6 | 13.5 |
| 2 | 2 | 3 | 40 | 7.8 | 2.7 | 19.6 | 6.6 | 4.2 | 17.1 |
| 2 | 2 | 3 | 80 | 11.3 | 2.8 | 21.6 | 7.9 | 5.3 | 27.5 |
| 3 | 1 | 1 | 10 | 4.7 | 1.9 | 11.6 | 3.9 | 2.7 | 12.6 |
| 3 | 1 | 1 | 40 | 7.3 | 4.4 | 15.0 | 8.0 | 3.4 | 17.3 |
| 3 | 1 | 1 | 80 | 8.5 | 3.9 | 22.1 | 10.9 | 5.8 | 37.8 |
| 3 | 1 | 2 | 10 | 4.5 | 1.1 | 8.4 | 4.4 | 2.8 | 10.7 |
| 3 | 1 | 2 | 40 | 6.0 | 2.1 | 13.9 | 7.4 | 5.0 | 13.7 |
| 3 | 1 | 2 | 80 | 12.5 | 2.3 | 18.4 | 10.6 | 5.2 | 21.0 |
| 3 | 1 | 3 | 10 | 4.0 | 1.5 | 7.1 | 4.7 | 3.2 | 7.4 |
| 3 | 1 | 3 | 40 | 4.4 | 1.1 | 18.3 | 8.4 | 5.0 | 16.1 |
| 3 | 1 | 3 | 80 | 8.4 | 1.8 | 26.4 | 12.5 | 5.7 | 19.3 |
| 3 | 2 | 1 | 10 | 7.0 | 1.0 | 17.7 | 6.2 | 2.9 | 12.6 |
| 3 | 2 | 1 | 40 | 7.1 | 3.1 | 18.2 | 7.8 | 5.7 | 19.9 |
| 3 | 2 | 1 | 80 | 8.9 | 1.4 | 20.7 | 11.4 | 6.8 | 33.1 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 7 Contact Forces (in Newton) at Tip of Thumb and 2$^{nd}$ Phalanx of Index Finger Measured for Wrench Task Simulations for Ten Female Subjects (Cont.)

| | | | | Tip of Thumb | | | 2nd Ph of IF | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TT | Median | Min | Max | Median | Min | Max |
| 3 | 2 | 2 | 10 | 3.2 | 1.5 | 8.3 | 5.7 | 2.4 | 13.0 |
| 3 | 2 | 2 | 40 | 4.8 | 1.8 | 10.6 | 9.0 | 2.4 | 17.4 |
| 3 | 2 | 2 | 80 | 8.7 | 4.5 | 19.6 | 9.4 | 5.5 | 23.9 |
| 3 | 2 | 3 | 10 | 4.0 | 0.6 | 8.4 | 4.4 | 2.9 | 13.6 |
| 3 | 2 | 3 | 40 | 5.1 | 1.7 | 9.5 | 6.2 | 2.4 | 15.0 |
| 3 | 2 | 3 | 80 | 10.4 | 1.3 | 13.1 | 8.5 | 2.9 | 21.9 |
| 4 | 1 | 1 | 10 | 4.0 | 1.2 | 16.7 | 3.5 | 2.5 | 11.0 |
| 4 | 1 | 1 | 40 | 6.5 | 4.1 | 38.2 | 7.3 | 3.7 | 15.5 |
| 4 | 1 | 1 | 80 | 12.2 | 3.6 | 34.9 | 11.4 | 7.2 | 26.9 |
| 4 | 1 | 2 | 10 | 5.4 | 0.9 | 14.4 | 3.8 | 1.7 | 10.5 |
| 4 | 1 | 2 | 40 | 10.7 | 3.2 | 19.6 | 6.9 | 2.3 | 19.0 |
| 4 | 1 | 2 | 80 | 13.0 | 4.6 | 26.6 | 8.9 | 3.8 | 27.6 |
| 4 | 1 | 3 | 10 | 5.0 | 1.6 | 13.7 | 3.5 | 2.0 | 9.0 |
| 4 | 1 | 3 | 40 | 9.4 | 2.9 | 14.3 | 5.9 | 2.5 | 13.2 |
| 4 | 1 | 3 | 80 | 9.1 | 2.7 | 28.2 | 10.2 | 4.6 | 27.3 |
| 4 | 2 | 1 | 10 | 5.0 | 2.0 | 12.2 | 4.2 | 2.0 | 12.3 |
| 4 | 2 | 1 | 40 | 5.6 | 1.8 | 23.4 | 6.6 | 2.8 | 15.5 |
| 4 | 2 | 1 | 80 | 9.2 | 2.2 | 35.1 | 11.4 | 6.1 | 30.1 |
| 4 | 2 | 2 | 10 | 4.5 | 1.8 | 16.3 | 4.2 | 2.7 | 14.2 |
| 4 | 2 | 2 | 40 | 7.6 | 1.3 | 18.9 | 5.6 | 1.3 | 24.6 |
| 4 | 2 | 2 | 80 | 10.4 | 1.3 | 29.9 | 9.0 | 2.0 | 36.6 |
| 4 | 2 | 3 | 10 | 5.3 | 2.1 | 12.2 | 4.1 | 3.1 | 10.6 |
| 4 | 2 | 3 | 40 | 4.4 | 1.3 | 14.4 | 6.5 | 2.7 | 20.3 |
| 4 | 2 | 3 | 80 | 7.1 | 1.4 | 26.3 | 8.2 | 2.4 | 25.2 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 7 Contact Forces (in Newton) at 2nd Phalanx of Middle Finger and H9 Area Measured for Wrench Task Simulations for Ten Female Subjects (Cont.)

| | | | | 2nd Ph of IF | | | Palm H9 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Glove** | **Th** | **Layer** | **TT** | **Median** | **Min** | **Max** | **Median** | **Min** | **Max** |
| 1 | --- | --- | 10 | 4.1 | 1.2 | 10.8 | 4.2 | 2.7 | 7.8 |
| 1 | --- | --- | 40 | 5.9 | 2.8 | 15.6 | 7.5 | 2.8 | 21.4 |
| 1 | --- | --- | 80 | 13.1 | 6.5 | 18.4 | 11.0 | 4.0 | 38.8 |
| 2 | 1 | 1 | 10 | 5.4 | 1.0 | 13.2 | 4.0 | 0.5 | 7.3 |
| 2 | 1 | 1 | 40 | 9.3 | 5.8 | 21.6 | 5.8 | 1.6 | 10.4 |
| 2 | 1 | 1 | 80 | 18.5 | 11.2 | 26.8 | 6.5 | 5.5 | 23.0 |
| 2 | 1 | 2 | 10 | 5.9 | 1.6 | 9.0 | 3.9 | 0.4 | 7.8 |
| 2 | 1 | 2 | 40 | 9.1 | 5.2 | 18.5 | 5.9 | 3.5 | 18.1 |
| 2 | 1 | 2 | 80 | 15.1 | 6.0 | 32.6 | 7.9 | 3.2 | 45.3 |
| 2 | 1 | 3 | 10 | 7.1 | 0.7 | 9.6 | 3.8 | 0.4 | 9.6 |
| 2 | 1 | 3 | 40 | 11.2 | 4.8 | 16.2 | 5.3 | 1.5 | 15.8 |
| 2 | 1 | 3 | 80 | 15.2 | 8.2 | 32.4 | 8.2 | 1.5 | 27.0 |
| 2 | 2 | 1 | 10 | 4.6 | 1.3 | 11.1 | 5.7 | 0.7 | 8.3 |
| 2 | 2 | 1 | 40 | 10.7 | 1.6 | 22.0 | 6.7 | 2.1 | 11.8 |
| 2 | 2 | 1 | 80 | 16.5 | 6.6 | 30.0 | 10.6 | 3.0 | 24.3 |
| 2 | 2 | 2 | 10 | 5.7 | 1.2 | 10.7 | 5.1 | 0.5 | 7.0 |
| 2 | 2 | 2 | 40 | 9.6 | 5.5 | 20.2 | 5.9 | 2.3 | 14.0 |
| 2 | 2 | 2 | 80 | 16.3 | 7.9 | 37.6 | 8.3 | 2.5 | 31.7 |
| 2 | 2 | 3 | 10 | 4.6 | 1.3 | 10.8 | 5.1 | 0.6 | 8.2 |
| 2 | 2 | 3 | 40 | 10.8 | 3.9 | 17.7 | 6.8 | 2.5 | 14.9 |
| 2 | 2 | 3 | 80 | 14.9 | 5.4 | 31.8 | 9.3 | 2.3 | 23.4 |
| 3 | 1 | 1 | 10 | 3.9 | 1.1 | 9.2 | 4.1 | 0.6 | 10.1 |
| 3 | 1 | 1 | 40 | 9.4 | 1.9 | 22.4 | 5.3 | 2.6 | 19.5 |
| 3 | 1 | 1 | 80 | 15.9 | 7.9 | 39.7 | 8.0 | 3.6 | 36.5 |
| 3 | 1 | 2 | 10 | 5.6 | 1.5 | 10.3 | 4.7 | 0.8 | 9.8 |
| 3 | 1 | 2 | 40 | 10.7 | 2.4 | 24.8 | 4.6 | 2.8 | 13.0 |
| 3 | 1 | 2 | 80 | 18.8 | 9.9 | 42.7 | 7.9 | 2.8 | 25.0 |
| 3 | 1 | 3 | 10 | 3.6 | 1.2 | 8.9 | 4.0 | 1.1 | 10.0 |
| 3 | 1 | 3 | 40 | 7.4 | 1.7 | 23.3 | 5.0 | 2.3 | 19.0 |
| 3 | 1 | 3 | 80 | 15.4 | 7.6 | 36.3 | 7.4 | 3.5 | 24.3 |
| 3 | 2 | 1 | 10 | 3.1 | 1.6 | 8.5 | 5.4 | 1.2 | 9.2 |
| 3 | 2 | 1 | 40 | 8.1 | 4.3 | 13.9 | 7.8 | 1.3 | 13.7 |
| 3 | 2 | 1 | 80 | 15.8 | 3.1 | 30.0 | 12.6 | 1.3 | 21.7 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 7 Contact Forces (in Newton) at 2nd Phalanx of Middle Finger and H9 Area Measured for Wrench Task Simulations for Ten Female Subjects (Cont.)

| | | | | 2nd Ph of IF | | | Palm H9 | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TT | Median | Min | Max | Median | Min | Max |
| 3 | 2 | 2 | 10 | 4.6 | 1.9 | 9.2 | 4.3 | 1.4 | 10.2 |
| 3 | 2 | 2 | 40 | 6.8 | 3.1 | 13.7 | 6.3 | 1.4 | 15.3 |
| 3 | 2 | 2 | 80 | 14.6 | 6.9 | 31.3 | 6.9 | 1.3 | 27.0 |
| 3 | 2 | 3 | 10 | 5.3 | 1.6 | 7.5 | 4.5 | 1.5 | 10.9 |
| 3 | 2 | 3 | 40 | 9.8 | 2.5 | 18.2 | 5.5 | 1.9 | 15.5 |
| 3 | 2 | 3 | 80 | 14.1 | 7.2 | 27.0 | 7.6 | 1.4 | 23.1 |
| 4 | 1 | 1 | 10 | 4.7 | 1.7 | 9.5 | 4.7 | 1.6 | 6.6 |
| 4 | 1 | 1 | 40 | 9.2 | 4.2 | 17.2 | 6.8 | 1.2 | 11.5 |
| 4 | 1 | 1 | 80 | 14.2 | 7.5 | 27.8 | 11.8 | 1.6 | 19.3 |
| 4 | 1 | 2 | 10 | 4.2 | 2.6 | 11.5 | 4.8 | 1.2 | 6.6 |
| 4 | 1 | 2 | 40 | 7.8 | 4.0 | 22.3 | 7.5 | 1.3 | 17.5 |
| 4 | 1 | 2 | 80 | 12.4 | 6.7 | 28.3 | 12.7 | 2.6 | 25.4 |
| 4 | 1 | 3 | 10 | 4.0 | 2.0 | 18.9 | 4.4 | 1.3 | 8.6 |
| 4 | 1 | 3 | 40 | 7.5 | 4.5 | 22.5 | 6.9 | 1.4 | 13.2 |
| 4 | 1 | 3 | 80 | 12.2 | 4.6 | 40.7 | 9.9 | 1.5 | 19.8 |
| 4 | 2 | 1 | 10 | 4.8 | 0.7 | 12.9 | 3.8 | 2.4 | 8.0 |
| 4 | 2 | 1 | 40 | 12.2 | 6.9 | 20.5 | 7.1 | 2.6 | 9.7 |
| 4 | 2 | 1 | 80 | 16.9 | 10.6 | 53.3 | 8.9 | 2.3 | 25.7 |
| 4 | 2 | 2 | 10 | 4.9 | 0.8 | 10.7 | 3.5 | 1.9 | 6.6 |
| 4 | 2 | 2 | 40 | 10.2 | 4.4 | 22.1 | 5.2 | 2.3 | 15.6 |
| 4 | 2 | 2 | 80 | 16.3 | 10.3 | 29.1 | 8.5 | 2.9 | 33.7 |
| 4 | 2 | 3 | 10 | 4.8 | 0.5 | 17.4 | 3.8 | 2.3 | 5.9 |
| 4 | 2 | 3 | 40 | 11.6 | 3.0 | 18.2 | 5.7 | 3.0 | 15.8 |
| 4 | 2 | 3 | 80 | 18.2 | 8.9 | 39.5 | 9.0 | 2.4 | 20.5 |

| | |
|---|---|
| Glove | 1: bare hand; 2: butyl; 3: hypalon; 4: neoprene |
| Th (Thickness) | 1: 0.015"; 2: 0.03" |
| Layer | 1: single layer; 2: double layer; 3: triple layer |
| TT (Target Torque) | Task demands in lbf-in (pound force – in) |

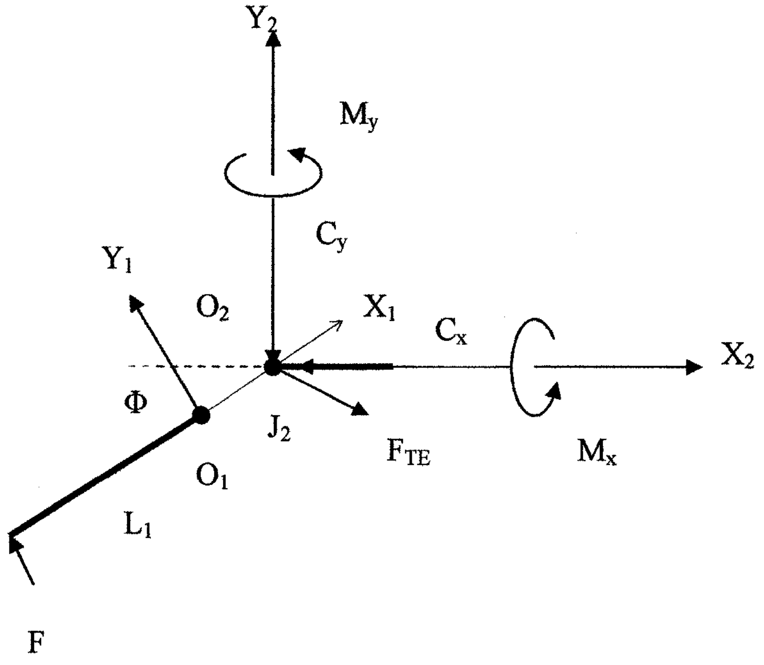
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 8 Subjective Hand Performance: Median, Minimum, and Maximum of the Static Two-Point Discrimination Distance (mm) and the Scores of Subjective Effects on Tingling, Comfort, and Preferences for Different Gloves of the Eleven Female Subjects

| | Tactility (mm) | | | Tingling (0-10) | | | Comfort (0-10) | | | Preferences (1-7) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Median** | **Min** | **Max** | **Median** | **Min** | **Max** | **Median** | **Min** | **Max** | **Median** | **Min** | **Max** |
| **Bare (rest)** | 3.0 | 2.0 | 4.0 | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bare (pinch)** | 3.0 | 2.0 | 4.0 | 2.0 | 2.0 | 2.5 | 1.0 | 1.0 | 1.0 | 1.5 | 1.0 | 2.0 |
| **B15** | 3.0 | 2.0 | 4.0 | 3.0 | 2.5 | 3.0 | 2.5 | 2.0 | 3.0 | 2.5 | 2.0 | 3.5 |
| **B30** | 3.0 | 2.0 | 5.0 | 4.0 | 3.5 | 4.5 | 5.0 | 5.0 | 6.0 | 4.0 | 4.0 | 5.0 |
| **H15** | 3.0 | 2.0 | 4.0 | 3.0 | 2.5 | 3.0 | 4.0 | 2.0 | 4.0 | 2.5 | 2.5 | 3.0 |
| **H30** | 4.0 | 3.0 | 5.0 | 4.5 | 4.0 | 5.5 | 6.0 | 5.0 | 7.0 | 5.0 | 4.5 | 5.5 |
| **N15** | 3.0 | 2.0 | 4.0 | 3.0 | 2.5 | 3.0 | 3.0 | 2.0 | 4.0 | 2.5 | 2.0 | 3.0 |
| **N30** | 4.0 | 3.0 | 5.0 | 5.0 | 5.0 | 6.0 | 7.0 | 6.0 | 7.0 | 5.5 | 5.0 | 6.0 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 9 Example for Constructing Force and Moment Equations



**Definition:**

| | |
|---|---|
| $O_1$ and $O_2$ | Coordinate systems with Z axis projected perpendicular out of the paper. |
| F | Externally applied force (contact force) perpendicular to the $X_1$ of $O_1$ coordinate system |
| $F_{TE}$ | unknown force in terminal extensor tendon |
| $C_x$, $C_y$, $C_z$ | unknown joint constraint forces, $C_z$: projected perpendicular into paper |
| $M_x$, $M_y$, $M_z$ | unknown joint constraint moments |
| $L_1$ | link length of the distal digit |
| $J_2$ | link length between axis1 -2 |
| $\Phi$ | flexion-extension angle |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$\theta = \psi = 0$ radioulnar deviation ($\theta$) and pronation-supination ($\psi$) angles

The x-axis is projected along the phalangeal or the metacarpal shaft, passing from the center of rotation to the center of the concave articular surface at the proximal end. The y-axis is projected dorsally, and the z-axis is projected radially for the right hand and ulnarly for the left hand.

**Force equations at $O_2$ coordinate system** (equation (4) with one tendon)

$(\alpha_i * F_{TE}) + C_x + (-F * \text{sine}(\Phi)) = 0$

$(\beta_i * F_{TE}) + C_y + (F * \text{cosine}(\Phi)) = 0$

$(\gamma_i * F_{TE}) + C_z = 0$

$\alpha_{TE}, \beta_{TE}, \gamma_{TE}$ = force potential parameters for TE provided by the author

Before constructing moment equations, use formula (6) to get the moment arms ($L_{x2}$, $L_{y2}$, $L_{z2}$) for the externally applied force F first.

$$\begin{bmatrix} -L1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} c\phi & s\phi & 0 \\ -s\phi & c\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} Lx2 \\ Ly2 \\ Lz2 \end{bmatrix} + \begin{bmatrix} J2 \\ 0 \\ 0 \end{bmatrix}$$

$L_{z2} = 0$

$L_{x2} = -(L1+J2) * \text{cosine}(\Phi)$

$L_{y2} = -(L1+J2) * \text{sine}(\Phi)$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Moment equations at $O_2$ coordinate system** (equation (5) with one tendon)

$a_{TE} * F_{TE} + M_x + L_{y2} * F_{z2} = 0$

$b_{TE} * F_{TE} + M_y + (-L_{x2} * F_{z2}) = 0$

$c_{TE} * F_{TE} + M_z + L_{x2}*F_{y2} - L_{y2}*F_{x2} = 0$

$a_{TE}$, $b_{TE}$, $c_{TE}$ = moment potential parameters for TE provided by the author

$F_{x2} = -F * \text{sine}(\Phi)$

$F_{y2} = F * \text{cosine}(\Phi)$

$F_{z2} = 0$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 10 Median Tendon and Muscle Forces (in Newton) of Thumb and Index Finger Measured for Roller Task Simulations for Ten Female Subjects

| | | | Thumb | | | | Index Finger | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | FPL | APB | ADD | TE | FP | RB | UB | RI | LU |
| 1 | --- | --- | 10 | 6.8 | 48.4 | 33.1 | 12.6 | 11.9 | 7.6 | 4.6 | 10.9 | 5.1 |
| 1 | --- | --- | 20 | 10.1 | 68.7 | 47.9 | 23.6 | 22.3 | 15.1 | 8.6 | 20.6 | 11.1 |
| 1 | --- | --- | 30 | 12.0 | 81.0 | 56.5 | 29.8 | 28.1 | 19.1 | 10.8 | 25.7 | 13.6 |
| 2 | 1 | 1 | 10 | 8.7 | 60.1 | 42.3 | 19.1 | 18.0 | 12.8 | 6.3 | 15.5 | 11.0 |
| 2 | 1 | 1 | 20 | 13.7 | 92.7 | 65.2 | 28.5 | 26.8 | 19.0 | 9.5 | 23.0 | 15.9 |
| 2 | 1 | 1 | 30 | 20.8 | 139.7 | 97.8 | 35.8 | 33.7 | 23.7 | 12.1 | 29.2 | 20.3 |
| 2 | 1 | 2 | 10 | 8.6 | 59.7 | 42.1 | 23.7 | 22.3 | 15.7 | 8.0 | 18.9 | 12.6 |
| 2 | 1 | 2 | 20 | 11.3 | 76.9 | 54.0 | 35.8 | 33.7 | 23.7 | 12.1 | 28.4 | 18.6 |
| 2 | 1 | 2 | 30 | 19.3 | 127.4 | 89.0 | 42.5 | 40.1 | 28.1 | 14.4 | 34.3 | 23.4 |
| 2 | 1 | 3 | 10 | 7.1 | 49.5 | 34.9 | 26.6 | 25.1 | 17.7 | 9.0 | 21.4 | 13.9 |
| 2 | 1 | 3 | 20 | 11.0 | 73.9 | 52.1 | 36.0 | 33.9 | 23.9 | 12.1 | 29.2 | 19.8 |
| 2 | 1 | 3 | 30 | 17.2 | 114.5 | 80.2 | 38.4 | 36.2 | 25.5 | 12.9 | 31.0 | 21.7 |
| 2 | 2 | 1 | 10 | 8.8 | 61.2 | 43.3 | 21.7 | 20.4 | 14.6 | 7.0 | 16.9 | 12.2 |
| 2 | 2 | 1 | 20 | 12.9 | 87.5 | 61.7 | 34.1 | 32.2 | 23.1 | 11.1 | 26.4 | 18.7 |
| 2 | 2 | 1 | 30 | 18.3 | 121.0 | 85.1 | 39.6 | 37.4 | 26.9 | 12.8 | 30.6 | 21.7 |
| 2 | 2 | 2 | 10 | 8.8 | 60.5 | 42.7 | 20.4 | 19.2 | 13.8 | 6.5 | 16.0 | 12.2 |
| 2 | 2 | 2 | 20 | 12.6 | 85.1 | 60.0 | 31.9 | 30.1 | 21.7 | 10.2 | 24.8 | 18.2 |
| 2 | 2 | 2 | 30 | 18.1 | 122.2 | 86.3 | 39.3 | 37.0 | 26.7 | 12.6 | 30.1 | 21.8 |
| 2 | 2 | 3 | 10 | 7.6 | 53.8 | 38.0 | 21.1 | 19.9 | 14.2 | 6.9 | 16.4 | 11.9 |
| 2 | 2 | 3 | 20 | 12.0 | 81.6 | 57.5 | 31.1 | 29.3 | 21.2 | 9.9 | 24.0 | 17.8 |
| 2 | 2 | 3 | 30 | 16.3 | 111.6 | 78.5 | 37.6 | 35.5 | 25.5 | 12.2 | 28.7 | 19.8 |
| 3 | 1 | 1 | 10 | 8.2 | 57.1 | 40.2 | 25.3 | 23.9 | 16.7 | 8.6 | 20.4 | 12.8 |
| 3 | 1 | 1 | 20 | 12.8 | 87.6 | 61.7 | 31.9 | 30.1 | 21.2 | 10.7 | 25.8 | 17.4 |
| 3 | 1 | 1 | 30 | 17.7 | 118.8 | 83.6 | 41.3 | 39.0 | 27.2 | 14.1 | 33.0 | 20.8 |
| 3 | 1 | 2 | 10 | 8.3 | 58.0 | 40.5 | 24.2 | 22.8 | 16.0 | 8.2 | 19.6 | 13.3 |
| 3 | 1 | 2 | 20 | 14.4 | 97.9 | 68.7 | 34.4 | 32.4 | 22.7 | 11.7 | 27.7 | 18.2 |
| 3 | 1 | 2 | 30 | 17.5 | 117.0 | 82.5 | 45.4 | 42.8 | 29.9 | 15.5 | 35.9 | 22.8 |
| 3 | 1 | 3 | 10 | 8.1 | 55.5 | 39.1 | 21.4 | 20.2 | 14.2 | 7.2 | 17.2 | 11.9 |
| 3 | 1 | 3 | 20 | 12.3 | 82.5 | 58.0 | 28.5 | 26.8 | 18.8 | 9.7 | 23.3 | 15.4 |
| 3 | 1 | 3 | 30 | 18.4 | 123.6 | 87.0 | 37.3 | 35.1 | 24.5 | 12.7 | 29.9 | 18.7 |
| 3 | 2 | 1 | 10 | 7.7 | 54.1 | 37.9 | 24.2 | 22.8 | 16.2 | 8.0 | 19.2 | 12.7 |
| 3 | 2 | 1 | 20 | 13.4 | 92.0 | 64.5 | 30.1 | 28.4 | 20.2 | 9.9 | 24.1 | 16.2 |
| 3 | 2 | 1 | 30 | 17.6 | 119.6 | 84.1 | 42.7 | 40.3 | 28.6 | 14.1 | 33.0 | 20.5 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 10 Median Tendon and Muscle Forces (in Newton) of Thumb and Index Finger Measured for Roller Task Simulations for Ten Female Subjects (Cont.)

| | | | | | Thumb | | | | Index Finger | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Glove** | **Th** | **Layer** | **TF** | **FPL** | **APB** | **ADD** | **TE** | **FP** | **RB** | **UB** | **RI** | **LU** |
| 3 | 2 | 2 | 10 | 9.3 | 65.4 | 46.0 | 23.8 | 22.4 | 16.0 | 7.8 | 18.5 | 12.5 |
| 3 | 2 | 2 | 20 | 15.3 | 104.7 | 73.9 | 30.5 | 28.8 | 20.6 | 9.9 | 24.0 | 17.7 |
| 3 | 2 | 2 | 30 | 19.4 | 131.0 | 92.3 | 43.7 | 41.1 | 29.3 | 14.3 | 34.0 | 23.4 |
| 3 | 2 | 3 | 10 | 6.8 | 48.9 | 34.4 | 17.9 | 16.9 | 11.9 | 5.9 | 14.2 | 9.1 |
| 3 | 2 | 3 | 20 | 12.7 | 88.8 | 62.4 | 28.7 | 27.0 | 19.2 | 9.4 | 22.6 | 14.9 |
| 3 | 2 | 3 | 30 | 17.9 | 122.6 | 86.5 | 40.8 | 38.4 | 27.4 | 13.4 | 31.9 | 21.1 |
| 4 | 1 | 1 | 10 | 8.4 | 58.4 | 41.0 | 23.0 | 21.7 | 15.2 | 7.8 | 18.5 | 12.6 |
| 4 | 1 | 1 | 20 | 12.6 | 87.0 | 61.1 | 30.3 | 28.6 | 20.1 | 10.3 | 24.8 | 16.7 |
| 4 | 1 | 1 | 30 | 16.0 | 107.3 | 75.1 | 44.5 | 41.9 | 29.4 | 15.1 | 36.3 | 24.7 |
| 4 | 1 | 2 | 10 | 7.3 | 52.6 | 37.1 | 22.8 | 21.5 | 15.1 | 7.7 | 18.5 | 12.2 |
| 4 | 1 | 2 | 20 | 14.5 | 98.4 | 69.0 | 33.0 | 31.1 | 21.8 | 11.2 | 26.8 | 17.3 |
| 4 | 1 | 2 | 30 | 16.9 | 116.5 | 82.5 | 42.7 | 40.2 | 28.1 | 14.6 | 34.7 | 23.3 |
| 4 | 1 | 3 | 10 | 7.8 | 55.0 | 38.5 | 19.8 | 18.7 | 13.1 | 6.7 | 15.9 | 10.2 |
| 4 | 1 | 3 | 20 | 11.3 | 77.7 | 54.5 | 25.4 | 23.9 | 16.8 | 8.6 | 20.7 | 14.0 |
| 4 | 1 | 3 | 30 | 14.6 | 99.4 | 70.1 | 39.7 | 37.4 | 26.3 | 13.4 | 31.8 | 22.1 |
| 4 | 2 | 1 | 10 | 7.7 | 54.0 | 38.0 | 24.3 | 22.9 | 16.1 | 8.2 | 19.2 | 12.6 |
| 4 | 2 | 1 | 20 | 11.8 | 80.5 | 56.6 | 34.0 | 32.0 | 22.6 | 11.4 | 26.8 | 17.2 |
| 4 | 2 | 1 | 30 | 13.8 | 96.2 | 67.1 | 41.8 | 39.4 | 27.9 | 13.9 | 33.6 | 22.0 |
| 4 | 2 | 2 | 10 | 7.2 | 50.8 | 35.8 | 22.8 | 21.5 | 15.2 | 7.6 | 17.9 | 12.3 |
| 4 | 2 | 2 | 20 | 11.4 | 78.4 | 55.0 | 32.4 | 30.5 | 21.6 | 10.8 | 25.7 | 17.2 |
| 4 | 2 | 2 | 30 | 18.1 | 122.4 | 85.8 | 39.7 | 37.4 | 26.4 | 13.3 | 32.3 | 21.3 |
| 4 | 2 | 3 | 10 | 6.9 | 48.4 | 34.1 | 21.9 | 20.6 | 14.7 | 7.2 | 17.2 | 12.0 |
| 4 | 2 | 3 | 20 | 11.3 | 76.9 | 54.3 | 32.3 | 30.4 | 21.4 | 10.9 | 25.4 | 15.7 |
| 4 | 2 | 3 | 30 | 12.3 | 84.5 | 59.2 | 39.3 | 37.1 | 26.1 | 13.2 | 31.0 | 19.8 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 10 Median Tendon and Muscle Forces (in Newton) of Middle and Ring Fingers Measured for Roller Task Simulations for Ten Female Subjects (Cont.)

| | | | | Middle Finger | | | | | Ring Finger | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | TE | FP | RB | UB | RI | TE | FP | RB | UB | RI |
| 1 | --- | --- | 10 | 23.7 | 27.2 | 14.4 | 9.2 | 12.0 | 28.1 | 28.4 | 14.1 | 13.9 | 3.6 |
| 1 | --- | --- | 20 | 34.6 | 38.5 | 21.0 | 13.5 | 14.7 | 49.4 | 51.3 | 24.9 | 24.5 | 8.5 |
| 1 | --- | --- | 30 | 57.8 | 64.4 | 35.2 | 22.6 | 24.3 | 74.3 | 77.7 | 37.4 | 36.9 | 12.8 |
| 2 | 1 | 1 | 10 | 32.8 | 36.7 | 20.0 | 12.8 | 14.7 | 24.2 | 25.5 | 12.2 | 12.0 | 3.7 |
| 2 | 1 | 1 | 20 | 40.6 | 45.2 | 24.7 | 15.9 | 17.3 | 37.0 | 38.6 | 18.6 | 18.4 | 5.2 |
| 2 | 1 | 1 | 30 | 48.5 | 53.7 | 29.5 | 19.0 | 19.7 | 48.8 | 51.1 | 24.6 | 24.2 | 6.1 |
| 2 | 1 | 2 | 10 | 34.9 | 38.7 | 21.3 | 13.7 | 15.7 | 25.7 | 27.0 | 12.9 | 12.7 | 4.0 |
| 2 | 1 | 2 | 20 | 44.0 | 48.7 | 26.8 | 17.2 | 18.5 | 48.9 | 50.9 | 24.6 | 24.3 | 6.5 |
| 2 | 1 | 2 | 30 | 51.0 | 56.5 | 31.0 | 19.9 | 20.4 | 63.7 | 66.1 | 32.1 | 31.6 | 8.4 |
| 2 | 1 | 3 | 10 | 23.9 | 26.5 | 14.6 | 9.4 | 10.2 | 20.7 | 21.5 | 10.4 | 10.3 | 2.9 |
| 2 | 1 | 3 | 20 | 34.9 | 38.5 | 21.2 | 13.6 | 14.5 | 35.9 | 37.0 | 18.1 | 17.8 | 4.5 |
| 2 | 1 | 3 | 30 | 49.5 | 54.9 | 30.2 | 19.4 | 20.2 | 57.7 | 60.1 | 29.1 | 28.7 | 7.3 |
| 2 | 2 | 1 | 10 | 32.6 | 36.0 | 19.8 | 12.7 | 14.1 | 26.1 | 26.7 | 13.2 | 13.0 | 3.1 |
| 2 | 2 | 1 | 20 | 40.8 | 44.9 | 24.8 | 15.9 | 17.1 | 33.3 | 34.6 | 16.8 | 16.6 | 4.1 |
| 2 | 2 | 1 | 30 | 51.1 | 56.3 | 31.1 | 20.0 | 21.3 | 51.2 | 53.3 | 25.8 | 25.4 | 6.4 |
| 2 | 2 | 2 | 10 | 37.9 | 41.5 | 23.1 | 14.8 | 15.8 | 26.3 | 27.5 | 13.2 | 13.0 | 3.4 |
| 2 | 2 | 2 | 20 | 41.5 | 45.4 | 25.2 | 16.2 | 17.1 | 37.9 | 39.5 | 19.1 | 18.8 | 4.9 |
| 2 | 2 | 2 | 30 | 49.5 | 55.0 | 30.2 | 19.4 | 20.2 | 70.2 | 73.8 | 35.3 | 34.8 | 9.2 |
| 2 | 2 | 3 | 10 | 35.0 | 38.8 | 21.3 | 13.7 | 14.9 | 25.6 | 26.7 | 12.9 | 12.7 | 3.3 |
| 2 | 2 | 3 | 20 | 45.8 | 50.6 | 27.9 | 17.9 | 19.1 | 34.9 | 36.5 | 17.6 | 17.3 | 4.4 |
| 2 | 2 | 3 | 30 | 49.8 | 55.0 | 30.3 | 19.5 | 20.6 | 59.6 | 61.8 | 30.0 | 29.6 | 7.7 |
| 3 | 1 | 1 | 10 | 28.0 | 31.0 | 17.0 | 10.9 | 11.8 | 19.4 | 20.3 | 9.8 | 9.6 | 2.9 |
| 3 | 1 | 1 | 20 | 38.6 | 42.8 | 23.5 | 15.1 | 17.1 | 26.4 | 27.4 | 13.3 | 13.1 | 3.9 |
| 3 | 1 | 1 | 30 | 53.3 | 58.6 | 32.5 | 20.8 | 22.2 | 42.8 | 44.4 | 21.5 | 21.2 | 6.2 |
| 3 | 1 | 2 | 10 | 36.1 | 40.2 | 22.0 | 14.1 | 16.3 | 18.9 | 19.9 | 9.5 | 9.4 | 2.6 |
| 3 | 1 | 2 | 20 | 35.3 | 39.1 | 21.5 | 13.8 | 15.1 | 31.0 | 32.3 | 15.6 | 15.4 | 4.9 |
| 3 | 1 | 2 | 30 | 55.5 | 61.1 | 33.8 | 21.7 | 24.3 | 40.9 | 42.3 | 20.6 | 20.3 | 6.0 |
| 3 | 1 | 3 | 10 | 28.7 | 31.9 | 17.5 | 11.2 | 13.0 | 20.2 | 21.2 | 10.2 | 10.0 | 2.9 |
| 3 | 1 | 3 | 20 | 39.6 | 43.9 | 24.1 | 15.5 | 17.7 | 26.5 | 27.5 | 13.4 | 13.2 | 4.0 |
| 3 | 1 | 3 | 30 | 43.8 | 48.2 | 26.7 | 17.1 | 18.8 | 38.3 | 39.8 | 19.3 | 19.0 | 6.1 |
| 3 | 2 | 1 | 10 | 28.8 | 31.7 | 17.5 | 11.3 | 12.2 | 28.6 | 30.4 | 14.4 | 14.2 | 2.8 |
| 3 | 2 | 1 | 20 | 34.1 | 37.7 | 20.8 | 13.3 | 14.1 | 30.8 | 32.3 | 15.5 | 15.3 | 3.3 |
| 3 | 2 | 1 | 30 | 44.8 | 49.5 | 27.3 | 17.5 | 19.4 | 53.9 | 55.6 | 27.1 | 26.7 | 4.9 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 10 Median Tendon and Muscle Forces (in Newton) of Middle and Ring Fingers Measured for Roller Task Simulations for Ten Female Subjects (Cont.)

| | | | | Middle Finger | | | | | Ring Finger | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Glove** | **Th** | **Layer** | **TF** | **TE** | **FP** | **RB** | **UB** | **RI** | **TE** | **FP** | **RB** | **UB** | **RI** |
| 3 | 2 | 2 | 10 | 26.6 | 29.5 | 16.2 | 10.4 | 11.4 | 27.1 | 28.4 | 13.6 | 13.4 | 2.8 |
| 3 | 2 | 2 | 20 | 33.6 | 37.2 | 20.5 | 13.2 | 14.4 | 33.9 | 35.3 | 17.1 | 16.8 | 3.6 |
| 3 | 2 | 2 | 30 | 45.2 | 49.7 | 27.5 | 17.7 | 18.6 | 52.6 | 54.3 | 26.5 | 26.1 | 5.5 |
| 3 | 2 | 3 | 10 | 43.0 | 47.1 | 26.2 | 16.8 | 18.1 | 29.9 | 31.3 | 15.0 | 14.8 | 3.0 |
| 3 | 2 | 3 | 20 | 32.3 | 35.7 | 19.7 | 12.6 | 14.0 | 34.6 | 36.0 | 17.4 | 17.2 | 3.5 |
| 3 | 2 | 3 | 30 | 40.6 | 44.8 | 24.7 | 15.9 | 17.2 | 48.0 | 49.8 | 24.2 | 23.8 | 5.3 |
| 4 | 1 | 1 | 10 | 27.1 | 30.2 | 16.5 | 10.6 | 13.1 | 29.4 | 30.7 | 14.8 | 14.6 | 3.5 |
| 4 | 1 | 1 | 20 | 34.4 | 38.4 | 20.9 | 13.4 | 15.5 | 36.5 | 38.0 | 18.4 | 18.1 | 4.0 |
| 4 | 1 | 1 | 30 | 37.4 | 41.8 | 22.8 | 14.6 | 18.3 | 54.8 | 57.9 | 27.6 | 27.2 | 7.4 |
| 4 | 1 | 2 | 10 | 32.5 | 36.3 | 19.8 | 12.7 | 14.9 | 35.3 | 37.3 | 17.8 | 17.5 | 4.0 |
| 4 | 1 | 2 | 20 | 28.7 | 32.1 | 17.5 | 11.2 | 13.8 | 42.6 | 44.3 | 21.5 | 21.2 | 5.0 |
| 4 | 1 | 2 | 30 | 48.5 | 54.1 | 29.5 | 19.0 | 20.3 | 70.1 | 72.9 | 35.3 | 34.8 | 7.0 |
| 4 | 1 | 3 | 10 | 27.2 | 30.4 | 16.6 | 10.6 | 12.9 | 34.0 | 35.6 | 17.1 | 16.9 | 4.2 |
| 4 | 1 | 3 | 20 | 38.0 | 41.9 | 23.1 | 14.8 | 17.0 | 48.6 | 50.9 | 24.5 | 24.1 | 5.8 |
| 4 | 1 | 3 | 30 | 44.7 | 50.2 | 27.2 | 17.5 | 19.7 | 62.2 | 64.7 | 31.3 | 30.9 | 8.5 |
| 4 | 2 | 1 | 10 | 37.9 | 42.0 | 23.1 | 14.8 | 15.9 | 30.5 | 31.9 | 15.4 | 15.1 | 3.0 |
| 4 | 2 | 1 | 20 | 44.9 | 49.7 | 27.3 | 17.6 | 18.0 | 43.2 | 45.1 | 21.7 | 21.4 | 4.0 |
| 4 | 2 | 1 | 30 | 61.5 | 68.4 | 37.5 | 24.1 | 24.9 | 68.6 | 72.2 | 34.5 | 34.1 | 5.8 |
| 4 | 2 | 2 | 10 | 44.6 | 49.6 | 27.2 | 17.5 | 18.5 | 43.6 | 46.0 | 21.9 | 21.6 | 3.8 |
| 4 | 2 | 2 | 20 | 53.8 | 59.7 | 32.8 | 21.1 | 21.8 | 43.3 | 45.7 | 21.8 | 21.5 | 3.8 |
| 4 | 2 | 2 | 30 | 70.3 | 78.2 | 42.8 | 27.5 | 28.5 | 73.8 | 77.4 | 37.2 | 36.7 | 6.2 |
| 4 | 2 | 3 | 10 | 38.8 | 43.1 | 23.6 | 15.2 | 15.9 | 35.2 | 37.0 | 17.7 | 17.5 | 3.1 |
| 4 | 2 | 3 | 20 | 50.3 | 55.6 | 30.6 | 19.7 | 20.3 | 44.3 | 46.3 | 22.3 | 22.0 | 4.2 |
| 4 | 2 | 3 | 30 | 60.1 | 66.5 | 36.6 | 23.5 | 24.0 | 77.6 | 81.6 | 39.1 | 38.5 | 7.3 |

| | |
|---|---|
| Glove | 1: bare hand; 2: butyl; 3: hypalon; 4: neoprene |
| Th (Thickness) | 1: 0.015"; 2: 0.03" |
| Layer | 1: single layer; 2: double layer; 3: triple layer |
| TF (Target Force) | Task demands in Newton |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 11 Median Tendon and Muscle Forces (in Newton) of Thumb and Index Finger Measured for Tweezers Task Simulations for Eleven Female Subjects

|  |  |  |  | Thumb |  |  | Index Finger |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | FPL | APB | ADD | TE | FP | RB | UB | RI |
| 1 | --- | --- | 5 | 4.6 | 34.2 | 22.6 | 18.8 | 23.9 | 10.6 | 8.2 | 11.8 |
| 1 | --- | --- | 10 | 10.3 | 67.0 | 48.9 | 34.8 | 44.5 | 19.6 | 15.2 | 21.8 |
| 1 | --- | --- | 15 | 12.7 | 90.7 | 60.4 | 57.5 | 79.6 | 32.4 | 25.1 | 36.1 |
| 2 | 1 | 1 | 5 | 7.4 | 43.0 | 28.7 | 23.0 | 29.8 | 13.0 | 10.1 | 13.3 |
| 2 | 1 | 1 | 10 | 15.1 | 112.2 | 74.8 | 47.9 | 63.8 | 26.9 | 20.9 | 30.8 |
| 2 | 1 | 1 | 15 | 24.7 | 171.4 | 122.2 | 76.2 | 109.1 | 42.9 | 33.3 | 52.3 |
| 2 | 1 | 2 | 5 | 6.7 | 43.8 | 29.8 | 22.9 | 29.4 | 12.9 | 10.0 | 14.3 |
| 2 | 1 | 2 | 10 | 14.3 | 94.4 | 66.3 | 43.8 | 58.9 | 24.6 | 19.1 | 31.1 |
| 2 | 1 | 2 | 15 | 19.9 | 142.1 | 94.7 | 76.2 | 97.4 | 42.9 | 33.3 | 44.3 |
| 2 | 1 | 3 | 5 | 5.9 | 37.3 | 26.6 | 22.9 | 30.2 | 12.9 | 10.0 | 15.4 |
| 2 | 1 | 3 | 10 | 13.8 | 86.1 | 56.6 | 48.0 | 62.7 | 27.0 | 21.0 | 26.7 |
| 2 | 1 | 3 | 15 | 18.1 | 124.3 | 87.6 | 71.7 | 100.9 | 40.4 | 31.4 | 41.4 |
| 2 | 2 | 1 | 5 | 5.7 | 42.4 | 28.7 | 28.9 | 36.2 | 16.3 | 11.3 | 16.5 |
| 2 | 2 | 1 | 10 | 15.1 | 88.9 | 60.9 | 59.7 | 76.5 | 33.6 | 26.1 | 34.3 |
| 2 | 2 | 1 | 15 | 20.6 | 141.8 | 94.5 | 102.8 | 132.2 | 57.9 | 45.0 | 61.4 |
| 2 | 2 | 2 | 5 | 6.1 | 35.7 | 25.8 | 23.8 | 32.9 | 13.4 | 10.2 | 14.6 |
| 2 | 2 | 2 | 10 | 13.1 | 108.7 | 70.5 | 53.9 | 73.3 | 30.3 | 23.6 | 36.6 |
| 2 | 2 | 2 | 15 | 24.2 | 197.2 | 132.3 | 79.3 | 101.6 | 44.6 | 34.7 | 46.3 |
| 2 | 2 | 3 | 5 | 6.2 | 35.0 | 24.6 | 24.2 | 32.4 | 13.6 | 10.3 | 14.2 |
| 2 | 2 | 3 | 10 | 13.2 | 87.3 | 57.4 | 54.2 | 69.7 | 30.5 | 23.0 | 30.4 |
| 2 | 2 | 3 | 15 | 24.6 | 162.7 | 114.6 | 72.2 | 94.0 | 40.6 | 31.6 | 43.1 |
| 3 | 1 | 1 | 5 | 6.3 | 40.6 | 27.6 | 27.0 | 36.0 | 15.2 | 11.8 | 16.3 |
| 3 | 1 | 1 | 10 | 13.9 | 107.8 | 70.9 | 49.0 | 61.8 | 27.6 | 21.4 | 28.6 |
| 3 | 1 | 1 | 15 | 18.4 | 133.2 | 87.8 | 80.8 | 103.5 | 45.5 | 35.3 | 55.1 |
| 3 | 1 | 2 | 5 | 7.5 | 52.2 | 34.8 | 25.3 | 32.5 | 14.3 | 11.1 | 14.8 |
| 3 | 1 | 2 | 10 | 14.1 | 103.5 | 68.6 | 54.2 | 69.7 | 30.5 | 23.7 | 33.5 |
| 3 | 1 | 2 | 15 | 17.4 | 124.6 | 83.1 | 80.3 | 102.9 | 45.2 | 35.1 | 49.2 |
| 3 | 1 | 3 | 5 | 5.6 | 40.5 | 26.7 | 22.7 | 29.3 | 12.8 | 9.9 | 15.6 |
| 3 | 1 | 3 | 10 | 14.3 | 70.7 | 46.6 | 49.8 | 64.8 | 28.0 | 21.8 | 32.9 |
| 3 | 1 | 3 | 15 | 15.9 | 117.0 | 78.5 | 62.9 | 79.2 | 35.4 | 27.5 | 45.4 |
| 3 | 2 | 1 | 5 | 7.6 | 49.5 | 31.8 | 27.4 | 33.2 | 15.4 | 12.0 | 16.1 |
| 3 | 2 | 1 | 10 | 15.2 | 90.9 | 58.9 | 56.4 | 72.5 | 31.7 | 24.7 | 32.4 |
| 3 | 2 | 1 | 15 | 25.4 | 176.6 | 117.6 | 77.9 | 99.1 | 43.8 | 34.0 | 47.9 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 11 Median Tendon and Muscle Forces (in Newton) of Thumb and Index Finger Measured for Tweezers Task Simulations for Eleven Female Subjects (Cont.)

| | | | | Thumb | | | | Index Finger | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TF | FPL | APB | ADD | TE | FP | RB | UB | RI |
| 3 | 2 | 2 | 5 | 7.7 | 48.3 | 32.6 | 27.2 | 37.9 | 15.3 | 11.9 | 15.7 |
| 3 | 2 | 2 | 10 | 14.4 | 99.9 | 71.2 | 52.2 | 67.1 | 29.4 | 22.8 | 34.9 |
| 3 | 2 | 2 | 15 | 23.7 | 164.4 | 113.6 | 76.4 | 100.6 | 43.0 | 33.4 | 52.1 |
| 3 | 2 | 3 | 5 | 6.4 | 46.3 | 31.0 | 25.9 | 33.3 | 14.6 | 11.3 | 15.2 |
| 3 | 2 | 3 | 10 | 13.6 | 102.2 | 70.7 | 49.5 | 65.8 | 27.9 | 21.7 | 35.0 |
| 3 | 2 | 3 | 15 | 24.0 | 150.2 | 105.2 | 77.2 | 91.2 | 43.5 | 33.8 | 47.4 |
| 4 | 1 | 1 | 5 | 7.2 | 41.2 | 26.7 | 24.9 | 31.6 | 14.0 | 10.9 | 15.2 |
| 4 | 1 | 1 | 10 | 13.5 | 85.1 | 56.5 | 54.4 | 69.7 | 30.6 | 23.8 | 31.6 |
| 4 | 1 | 1 | 15 | 17.0 | 157.5 | 106.2 | 78.3 | 106.6 | 44.1 | 34.2 | 46.8 |
| 4 | 1 | 2 | 5 | 6.0 | 41.5 | 28.6 | 29.5 | 37.5 | 16.6 | 12.9 | 18.6 |
| 4 | 1 | 2 | 10 | 10.4 | 81.4 | 54.6 | 46.4 | 65.2 | 26.1 | 20.3 | 33.8 |
| 4 | 1 | 2 | 15 | 22.2 | 140.3 | 91.8 | 72.2 | 100.9 | 40.6 | 31.6 | 49.1 |
| 4 | 1 | 3 | 5 | 5.7 | 39.7 | 26.6 | 25.4 | 32.8 | 14.3 | 11.1 | 17.3 |
| 4 | 1 | 3 | 10 | 11.0 | 71.9 | 48.3 | 49.4 | 61.3 | 27.8 | 21.6 | 31.3 |
| 4 | 1 | 3 | 15 | 16.7 | 119.7 | 79.8 | 76.6 | 98.9 | 43.1 | 33.5 | 45.1 |
| 4 | 2 | 1 | 5 | 6.4 | 50.7 | 33.7 | 26.2 | 32.5 | 14.7 | 11.4 | 15.4 |
| 4 | 2 | 1 | 10 | 16.7 | 94.3 | 63.7 | 49.9 | 61.0 | 28.1 | 21.8 | 29.0 |
| 4 | 2 | 1 | 15 | 22.8 | 162.8 | 108.5 | 68.7 | 88.6 | 38.7 | 30.0 | 48.2 |
| 4 | 2 | 2 | 5 | 5.1 | 37.0 | 25.9 | 35.8 | 45.5 | 20.1 | 15.6 | 21.4 |
| 4 | 2 | 2 | 10 | 10.3 | 74.9 | 49.2 | 69.9 | 89.9 | 39.3 | 30.6 | 43.4 |
| 4 | 2 | 2 | 15 | 15.7 | 117.4 | 76.1 | 88.8 | 114.2 | 50.0 | 38.8 | 48.2 |
| 4 | 2 | 3 | 5 | 5.4 | 40.6 | 29.3 | 24.4 | 31.1 | 13.8 | 10.7 | 15.6 |
| 4 | 2 | 3 | 10 | 13.2 | 75.6 | 49.0 | 54.3 | 69.1 | 30.6 | 23.7 | 34.3 |
| 4 | 2 | 3 | 15 | 19.5 | 128.7 | 86.8 | 67.6 | 86.8 | 38.0 | 29.5 | 45.1 |

| | |
|---|---|
| Glove | 1: bare hand; 2: butyl; 3: hypalon; 4: neoprene |
| Th (Thickness) | 1: 0.015"; 2: 0.03" |
| Layer | 1: single layer; 2: double layer; 3: triple layer |
| TF (Target Force) | Task demands in Newton |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 12 Median Tendon and Muscle Forces (in Newton) of Thumb and Index Finger Measured for Wrench Task Simulations for Ten Female Subjects

| | | | | Thumb | | | | Index Finger | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TT | FPL | APB | ADD | TE | FP | RB | UB | RI | LU |
| 1 | 0 | 0 | 10 | 4.8 | 30.2 | 21.6 | 7.5 | 7.1 | 5.2 | 2.4 | 5.3 | 4.5 |
| 1 | 0 | 0 | 40 | 9.3 | 49.7 | 34.9 | 18.4 | 17.4 | 12.3 | 6.1 | 15.0 | 9.6 |
| 1 | 0 | 0 | 80 | 10.9 | 60.7 | 43.1 | 25.9 | 24.4 | 17.2 | 8.7 | 21.4 | 13.1 |
| 2 | 1 | 1 | 10 | 7.5 | 41.0 | 28.7 | 10.6 | 10.0 | 7.0 | 3.6 | 8.4 | 5.9 |
| 2 | 1 | 1 | 40 | 12.2 | 65.7 | 46.0 | 17.8 | 16.8 | 11.7 | 6.1 | 14.0 | 8.8 |
| 2 | 1 | 1 | 80 | 18.8 | 106.0 | 74.8 | 24.2 | 22.8 | 16.1 | 8.2 | 19.1 | 12.9 |
| 2 | 1 | 2 | 10 | 9.3 | 50.0 | 35.7 | 11.0 | 10.4 | 7.2 | 3.8 | 8.8 | 5.7 |
| 2 | 1 | 2 | 40 | 11.0 | 58.9 | 41.7 | 16.0 | 15.1 | 10.6 | 5.4 | 12.4 | 8.7 |
| 2 | 1 | 2 | 80 | 16.2 | 88.7 | 62.6 | 21.9 | 20.6 | 14.5 | 7.4 | 17.0 | 11.8 |
| 2 | 1 | 3 | 10 | 8.7 | 45.6 | 32.2 | 12.2 | 11.5 | 8.1 | 4.1 | 9.6 | 6.5 |
| 2 | 1 | 3 | 40 | 13.0 | 69.6 | 49.0 | 17.2 | 16.2 | 11.4 | 5.8 | 13.5 | 9.9 |
| 2 | 1 | 3 | 80 | 16.3 | 88.3 | 62.1 | 21.6 | 20.4 | 14.4 | 7.2 | 16.8 | 12.6 |
| 2 | 2 | 1 | 10 | 7.0 | 39.0 | 27.3 | 10.1 | 9.5 | 6.8 | 3.3 | 7.4 | 5.6 |
| 2 | 2 | 1 | 40 | 13.5 | 73.4 | 51.6 | 19.6 | 18.5 | 13.3 | 6.3 | 14.7 | 10.9 |
| 2 | 2 | 1 | 80 | 17.2 | 94.2 | 65.9 | 28.4 | 26.8 | 19.0 | 9.4 | 20.7 | 14.3 |
| 2 | 2 | 2 | 10 | 8.0 | 43.9 | 30.8 | 12.2 | 11.5 | 8.2 | 4.1 | 9.2 | 6.5 |
| 2 | 2 | 2 | 40 | 11.3 | 61.8 | 43.2 | 16.9 | 16.0 | 11.6 | 5.3 | 12.3 | 10.1 |
| 2 | 2 | 2 | 80 | 15.8 | 87.9 | 61.5 | 23.6 | 22.3 | 16.2 | 7.4 | 17.0 | 13.5 |
| 2 | 2 | 3 | 10 | 7.6 | 42.6 | 29.7 | 13.4 | 12.6 | 8.9 | 4.5 | 10.1 | 7.0 |
| 2 | 2 | 3 | 40 | 11.3 | 64.3 | 44.9 | 17.7 | 16.7 | 12.2 | 5.6 | 13.0 | 10.0 |
| 2 | 2 | 3 | 80 | 14.5 | 79.5 | 55.7 | 25.7 | 24.2 | 17.6 | 8.1 | 19.0 | 14.4 |
| 3 | 1 | 1 | 10 | 6.8 | 37.8 | 26.6 | 12.5 | 11.7 | 8.3 | 4.2 | 9.6 | 6.3 |
| 3 | 1 | 1 | 40 | 9.7 | 54.3 | 38.1 | 20.0 | 18.8 | 13.3 | 6.7 | 15.7 | 10.0 |
| 3 | 1 | 1 | 80 | 11.8 | 66.7 | 46.6 | 26.8 | 25.3 | 17.8 | 9.0 | 21.9 | 14.0 |
| 3 | 1 | 2 | 10 | 5.8 | 32.2 | 22.6 | 11.2 | 10.5 | 7.4 | 3.7 | 8.9 | 5.8 |
| 3 | 1 | 2 | 40 | 8.2 | 46.2 | 32.6 | 17.0 | 16.0 | 11.4 | 5.7 | 13.2 | 9.1 |
| 3 | 1 | 2 | 80 | 13.7 | 75.6 | 53.0 | 24.9 | 23.5 | 16.7 | 8.2 | 19.6 | 13.5 |
| 3 | 1 | 3 | 10 | 4.7 | 26.2 | 18.4 | 10.4 | 9.8 | 6.9 | 3.5 | 8.2 | 5.5 |
| 3 | 1 | 3 | 40 | 7.3 | 41.8 | 29.5 | 18.9 | 17.8 | 12.6 | 6.3 | 15.0 | 10.3 |
| 3 | 1 | 3 | 80 | 12.1 | 66.1 | 46.5 | 25.4 | 23.9 | 17.0 | 8.4 | 19.9 | 13.9 |
| 3 | 2 | 1 | 10 | 8.7 | 50.1 | 35.5 | 14.0 | 13.2 | 9.2 | 4.8 | 11.5 | 7.4 |
| 3 | 2 | 1 | 40 | 10.4 | 56.9 | 40.2 | 20.3 | 19.1 | 13.4 | 6.9 | 16.6 | 10.1 |
| 3 | 2 | 1 | 80 | 10.6 | 59.8 | 42.1 | 29.7 | 28.0 | 19.8 | 9.9 | 23.9 | 15.0 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 12 Median Tendon and Muscle Forces (in Newton) of Thumb and Index Finger Measured for Wrench Task Simulations for Ten Female Subjects (Cont.)

| | | | | | Thumb | | | | Index Finger | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TT | FPL | APB | ADD | TE | FP | RB | UB | RI | LU |
| 3 | 2 | 2 | 10 | 4.8 | 27.1 | 18.9 | 13.3 | 12.5 | 8.8 | 4.5 | 10.6 | 6.9 |
| 3 | 2 | 2 | 40 | 7.1 | 40.1 | 28.4 | 19.9 | 18.7 | 13.1 | 6.7 | 16.0 | 10.3 |
| 3 | 2 | 2 | 80 | 12.4 | 68.3 | 47.9 | 22.4 | 21.1 | 15.0 | 7.4 | 17.9 | 12.0 |
| 3 | 2 | 3 | 10 | 5.0 | 28.4 | 19.8 | 12.3 | 11.6 | 8.2 | 4.1 | 10.0 | 6.7 |
| 3 | 2 | 3 | 40 | 6.0 | 34.1 | 23.9 | 14.7 | 13.9 | 9.8 | 5.0 | 12.0 | 7.8 |
| 3 | 2 | 3 | 80 | 10.6 | 58.7 | 41.0 | 21.8 | 20.5 | 14.5 | 7.3 | 17.4 | 11.3 |
| 4 | 1 | 1 | 10 | 8.0 | 43.2 | 30.1 | 10.8 | 10.2 | 7.1 | 3.7 | 8.4 | 5.1 |
| 4 | 1 | 1 | 40 | 14.6 | 80.1 | 57.0 | 18.2 | 17.2 | 12.1 | 6.1 | 14.0 | 9.0 |
| 4 | 1 | 1 | 80 | 19.9 | 106.7 | 74.8 | 30.6 | 28.8 | 20.3 | 10.3 | 23.6 | 15.4 |
| 4 | 1 | 2 | 10 | 8.3 | 45.4 | 31.7 | 10.7 | 10.0 | 7.0 | 3.7 | 8.2 | 5.1 |
| 4 | 1 | 2 | 40 | 13.2 | 71.8 | 50.3 | 17.9 | 16.9 | 11.9 | 6.0 | 13.6 | 9.0 |
| 4 | 1 | 2 | 80 | 17.6 | 97.6 | 68.5 | 25.3 | 23.9 | 16.8 | 8.5 | 19.3 | 12.1 |
| 4 | 1 | 3 | 10 | 7.9 | 43.0 | 30.0 | 9.6 | 9.0 | 6.3 | 3.3 | 7.4 | 4.5 |
| 4 | 1 | 3 | 40 | 11.1 | 62.1 | 43.7 | 14.8 | 14.0 | 9.8 | 5.0 | 11.2 | 6.9 |
| 4 | 1 | 3 | 80 | 14.4 | 81.5 | 57.5 | 22.5 | 21.2 | 14.8 | 7.7 | 18.2 | 10.5 |
| 4 | 2 | 1 | 10 | 7.1 | 38.9 | 27.3 | 10.7 | 10.1 | 7.0 | 3.7 | 8.6 | 5.1 |
| 4 | 2 | 1 | 40 | 9.1 | 51.6 | 36.6 | 16.8 | 15.9 | 11.0 | 5.8 | 13.7 | 7.8 |
| 4 | 2 | 1 | 80 | 17.5 | 91.7 | 64.2 | 27.3 | 25.7 | 17.9 | 9.4 | 22.7 | 13.2 |
| 4 | 2 | 2 | 10 | 7.3 | 41.1 | 29.0 | 11.6 | 10.9 | 7.5 | 4.1 | 9.3 | 5.4 |
| 4 | 2 | 2 | 40 | 9.6 | 53.0 | 37.6 | 17.5 | 16.4 | 11.5 | 6.0 | 14.1 | 8.4 |
| 4 | 2 | 2 | 80 | 14.6 | 81.1 | 57.5 | 24.9 | 23.5 | 16.5 | 8.4 | 20.0 | 12.1 |
| 4 | 2 | 3 | 10 | 7.3 | 39.1 | 27.6 | 12.1 | 11.4 | 7.9 | 4.2 | 9.9 | 5.8 |
| 4 | 2 | 3 | 40 | 7.2 | 39.9 | 28.2 | 19.1 | 18.0 | 12.5 | 6.5 | 15.2 | 8.8 |
| 4 | 2 | 3 | 80 | 10.5 | 60.2 | 42.8 | 22.4 | 21.1 | 14.7 | 7.7 | 18.2 | 10.3 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 12 Median Tendon and Muscle Forces (in Newton) of Middle Finger Measured for Wrench Task Simulations for Ten Female Subjects (Cont.)

| | | | Middle Finger | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TT | TE | FP | RB | UB | RI | LU |
| 1 | 0 | 0 | 10 | 10.4 | 9.3 | 6.4 | 3.9 | 6.8 | 1.8 |
| 1 | 0 | 0 | 40 | 16.7 | 14.9 | 10.5 | 6.3 | 13.0 | 3.6 |
| 1 | 0 | 0 | 80 | 32.5 | 28.9 | 20.2 | 12.3 | 24.1 | 6.1 |
| 2 | 1 | 1 | 10 | 12.2 | 10.9 | 7.6 | 4.6 | 9.9 | 2.9 |
| 2 | 1 | 1 | 40 | 25.5 | 22.7 | 15.9 | 9.6 | 20.1 | 5.5 |
| 2 | 1 | 1 | 80 | 43.7 | 38.9 | 27.3 | 16.4 | 33.8 | 9.1 |
| 2 | 1 | 2 | 10 | 12.8 | 11.4 | 8.0 | 4.8 | 10.2 | 3.1 |
| 2 | 1 | 2 | 40 | 24.4 | 21.7 | 15.3 | 9.1 | 19.3 | 5.6 |
| 2 | 1 | 2 | 80 | 40.9 | 36.4 | 25.6 | 15.4 | 31.9 | 8.7 |
| 2 | 1 | 3 | 10 | 13.0 | 11.6 | 8.1 | 4.8 | 10.5 | 3.1 |
| 2 | 1 | 3 | 40 | 24.6 | 21.9 | 15.5 | 9.1 | 19.3 | 5.6 |
| 2 | 1 | 3 | 80 | 41.2 | 36.7 | 25.9 | 15.3 | 31.7 | 9.3 |
| 2 | 2 | 1 | 10 | 11.6 | 10.3 | 7.3 | 4.3 | 9.6 | 2.7 |
| 2 | 2 | 1 | 40 | 23.3 | 20.8 | 14.6 | 8.8 | 19.7 | 5.6 |
| 2 | 2 | 1 | 80 | 43.5 | 38.6 | 27.1 | 16.3 | 35.6 | 10.0 |
| 2 | 2 | 2 | 10 | 11.7 | 10.4 | 7.3 | 4.4 | 9.9 | 2.9 |
| 2 | 2 | 2 | 40 | 24.0 | 21.3 | 15.0 | 9.0 | 19.7 | 5.5 |
| 2 | 2 | 2 | 80 | 44.5 | 39.6 | 27.8 | 16.7 | 35.7 | 9.7 |
| 2 | 2 | 3 | 10 | 12.3 | 11.0 | 7.7 | 4.6 | 10.1 | 3.1 |
| 2 | 2 | 3 | 40 | 25.0 | 22.2 | 15.7 | 9.3 | 19.9 | 5.8 |
| 2 | 2 | 3 | 80 | 37.7 | 33.5 | 23.6 | 14.1 | 29.9 | 8.5 |
| 3 | 1 | 1 | 10 | 9.5 | 8.5 | 6.1 | 3.5 | 6.9 | 2.5 |
| 3 | 1 | 1 | 40 | 23.2 | 20.7 | 14.7 | 8.5 | 17.1 | 6.0 |
| 3 | 1 | 1 | 80 | 45.1 | 40.1 | 28.5 | 16.6 | 32.9 | 10.7 |
| 3 | 1 | 2 | 10 | 13.0 | 11.5 | 8.2 | 4.8 | 10.1 | 3.5 |
| 3 | 1 | 2 | 40 | 27.2 | 24.2 | 17.2 | 10.0 | 20.7 | 7.3 |
| 3 | 1 | 2 | 80 | 47.6 | 42.3 | 30.0 | 17.6 | 35.5 | 11.6 |
| 3 | 1 | 3 | 10 | 9.2 | 8.2 | 5.8 | 3.4 | 7.2 | 2.4 |
| 3 | 1 | 3 | 40 | 22.7 | 20.2 | 14.4 | 8.3 | 17.1 | 6.0 |
| 3 | 1 | 3 | 80 | 44.7 | 39.7 | 28.1 | 16.5 | 33.4 | 11.1 |
| 3 | 2 | 1 | 10 | 9.6 | 8.5 | 6.0 | 3.5 | 7.6 | 2.4 |
| 3 | 2 | 1 | 40 | 20.4 | 18.1 | 12.8 | 7.6 | 15.5 | 4.7 |
| 3 | 2 | 1 | 80 | 36.9 | 32.8 | 23.1 | 13.7 | 28.0 | 8.3 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 12 Median Tendon and Muscle Forces (in Newton) of Middle Finger Measured for Wrench Task Simulations for Ten Female Subjects (Cont.)

| | | | | Middle Finger | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Glove | Th | Layer | TT | TE | FP | RB | UB | RI | LU |
| 3 | 2 | 2 | 10 | 10.7 | 9.5 | 6.8 | 4.0 | 8.4 | 2.7 |
| 3 | 2 | 2 | 40 | 18.9 | 16.8 | 11.9 | 7.0 | 14.5 | 4.5 |
| 3 | 2 | 2 | 80 | 38.7 | 34.4 | 24.3 | 14.4 | 29.8 | 9.0 |
| 3 | 2 | 3 | 10 | 11.3 | 10.1 | 7.1 | 4.2 | 9.1 | 2.9 |
| 3 | 2 | 3 | 40 | 23.0 | 20.4 | 14.5 | 8.5 | 17.8 | 5.8 |
| 3 | 2 | 3 | 80 | 38.6 | 34.3 | 24.3 | 14.3 | 29.7 | 9.5 |
| 4 | 1 | 1 | 10 | 12.2 | 10.9 | 7.6 | 4.6 | 9.5 | 2.8 |
| 4 | 1 | 1 | 40 | 23.1 | 20.6 | 14.5 | 8.6 | 17.5 | 5.0 |
| 4 | 1 | 1 | 80 | 37.5 | 33.4 | 23.5 | 14.1 | 28.3 | 7.9 |
| 4 | 1 | 2 | 10 | 12.0 | 10.7 | 7.5 | 4.5 | 9.6 | 2.8 |
| 4 | 1 | 2 | 40 | 22.9 | 20.4 | 14.4 | 8.6 | 17.7 | 5.1 |
| 4 | 1 | 2 | 80 | 35.3 | 31.4 | 22.0 | 13.3 | 27.0 | 7.6 |
| 4 | 1 | 3 | 10 | 12.7 | 11.3 | 7.9 | 4.8 | 10.4 | 3.1 |
| 4 | 1 | 3 | 40 | 22.9 | 20.4 | 14.3 | 8.6 | 17.8 | 5.1 |
| 4 | 1 | 3 | 80 | 40.2 | 35.8 | 25.0 | 15.2 | 31.5 | 8.7 |
| 4 | 2 | 1 | 10 | 13.9 | 12.4 | 8.9 | 5.0 | 10.8 | 4.0 |
| 4 | 2 | 1 | 40 | 29.9 | 26.6 | 19.0 | 10.9 | 22.3 | 7.7 |
| 4 | 2 | 1 | 80 | 50.3 | 44.7 | 31.7 | 18.6 | 39.0 | 13.0 |
| 4 | 2 | 2 | 10 | 13.5 | 12.0 | 8.7 | 4.9 | 10.3 | 4.0 |
| 4 | 2 | 2 | 40 | 27.2 | 24.2 | 17.2 | 10.0 | 20.5 | 7.0 |
| 4 | 2 | 2 | 80 | 43.7 | 38.9 | 27.6 | 16.1 | 32.9 | 11.1 |
| 4 | 2 | 3 | 10 | 14.3 | 12.7 | 9.3 | 5.0 | 10.5 | 4.7 |
| 4 | 2 | 3 | 40 | 26.1 | 23.2 | 16.7 | 9.4 | 19.2 | 7.4 |
| 4 | 2 | 3 | 80 | 49.5 | 44.0 | 31.3 | 18.1 | 36.5 | 12.8 |

| | |
|---|---|
| Glove | 1: bare hand; 2: butyl; 3: hypalon; 4: neoprene |
| Th (Thickness) | 1: 0.015"; 2: 0.03" |
| Layer | 1: single layer; 2: double layer; 3: triple layer |
| TT (Target Torque) | Task demands in lbf-in (pound force – in) |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 13 Summary Results of Kolmogorov-Smirnov and Levene Tests for Evaluating the Effects of Glove and Task Demand on Tendon and Muscle Forces (Roller Tasks)

| **Roller** | | **Original Data** | | **Log10** | | **SQRT** | |
|---|---|---|---|---|---|---|---|
| **Digit** | | **KS** | **Levene** | **KS** | **Levene** | **KS** | **Levene** |
| **Thumb** | **FPL** | 1.47* | 2.76* | 0.56 | 1.38 | | |
| | **APB** | 1.34 | 2.09* | 0.70 | 1.48 | | |
| | **ADD** | 1.48* | 1.87* | 0.61 | 1.46 | | |
| **IF** | **TE** | 1.67* | 3.23* | 1.06 | 1.61 | | |
| | **FP** | 1.67* | 3.23* | 1.06 | 1.61 | | |
| | **RB** | 1.68* | 2.91* | 0.90 | 1.53 | | |
| | **UB** | 1.25 | 3.00* | 1.10 | 0.70 | | |
| | **RI** | 1.49* | 2.77* | 0.94 | 1.03 | | |
| | **LU** | 1.92* | 0.93 | 0.98 | 0.59 | | |
| **MF** | **TE** | 1.69* | 2.08* | 0.80 | 1.06 | | |
| | **FP** | 1.65* | 2.34* | 0.72 | 1.13 | | |
| | **RB** | 1.69* | 2.08* | 0.80 | 1.06 | | |
| | **UB** | 1.69* | 2.08* | 0.80 | 1.06 | | |
| | **RI** | 1.70* | 2.01* | 0.66 | 0.92 | | |
| **RF** | **TE** | 1.73* | 3.73* | 0.72 | 0.75 | | |
| | **FP** | 1.84* | 3.59* | 0.61 | 0.84 | | |
| | **RB** | 1.73* | 3.73* | 0.72 | 0.75 | | |
| | **UB** | 1.73* | 3.73* | 0.72 | 0.75 | | |
| | **RI** | 2.81* | 1.30 | 2.64* | 0.05 | 1.35 | 0.44 |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 13 Summary Results of Kolmogorov-Smirnov and Levene Tests for Evaluating the Effects of Glove and Task Demand on Tendon and Muscle Forces (Tweezers Tasks)

| **Tweezers** | | **Original Data** | | **Log10** | | **SQRT** | |
|---|---|---|---|---|---|---|---|
| **Digit** | | **KS** | **Levene** | **KS** | **Levene** | **KS** | **Levene** |
| **Th** | **FPL** | 1.97* | 6.30* | 0.69 | 1.96* | 1.36* | 3.69* |
| | **APB** | 1.95* | 4.67* | 0.95 | 1.52 | | |
| | **ADD** | 2.00* | 4.98* | 0.90 | 1.83* | 1.34 | 2.79* |
| **IF** | **TE** | 1.92* | 5.18* | 0.87 | 1.68* | 1.42* | 3.31* |
| | **FP** | 1.84* | 4.57* | 1.05 | 1.23 | | |
| | **RB** | 1.86* | 4.85* | 0.82 | 1.66* | 1.36* | 3.18* |
| | **UB** | 1.90* | 5.23* | 0.85 | 1.65* | 1.39* | 3.31* |
| | **RI** | 1.79* | 3.99* | 1.05 | 1.22 | | |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 13 Summary Results of Kolmogorov-Smirnov and Levene Tests for Evaluating the Effects of Glove and Task Demand on Tendon and Muscle Forces (Wrench Tasks)

| **Wrench** | | **Original Data** | | **Log10** | |
|---|---|---|---|---|---|
| **Digit** | | **KS** | **Levene** | **KS** | **Levene** |
| **Thumb** | **FPL** | 2.82* | 3.29* | 0.77 | 1.01 |
| | **APB** | 2.14* | 3.93* | 0.63 | 1.42 |
| | **ADD** | 2.24* | 3.93* | 0.60 | 1.38 |
| **IF** | **TE** | 2.01* | 1.89* | 0.89 | 0.45 |
| | **FP** | 2.01* | 1.89* | 0.89 | 0.45 |
| | **RB** | 2.05* | 1.89* | 0.81 | 0.48 |
| | **UB** | 2.19* | 1.82* | 0.94 | 0.36 |
| | **RI** | 2.39* | 1.57 | 0.85 | 0.42 |
| | **LU** | 2.02* | 2.86* | 0.66 | 1.11 |
| **MF** | **TE** | 1.67* | 3.49* | 0.70 | 0.72 |
| | **FP** | 1.67* | 3.49* | 0.70 | 0.72 |
| | **RB** | 1.58* | 3.66* | 0.75 | 0.79 |
| | **UB** | 1.85* | 3.22* | 0.90 | 0.59 |
| | **RI** | 1.62* | 2.66* | 0.91 | 0.85 |
| | **LU** | 1.90* | 3.49* | 1.04 | 1.33 |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 13 Summary Results of Kolmogorov-Smirnov and Levene Tests for Evaluating the Effects of Glove, Thickness, Layer, and Task Demand on Tendon and Muscle Forces (Roller Tasks)

| **Roller** | | **Original Data** | | **Log10** | | **SQRT** | |
|---|---|---|---|---|---|---|---|
| **Digit** | | **KS** | **Levene** | **KS** | **Levene** | **KS** | **Levene** |
| **Thumb** | **FPL** | 1.93* | 2.45* | 1.11 | 1.36 | | |
| | **APB** | 1.92* | 1.35* | 1.01 | 1.41* | 0.74 | 0.89 |
| | **ADD** | 2.05* | 1.17 | 0.90 | 1.31 | | |
| **IF** | **TE** | 2.65* | 2.28* | 1.08 | 0.93 | | |
| | **FP** | 2.65* | 2.28* | 1.08 | 0.93 | | |
| | **RB** | 2.62* | 2.09* | 0.88 | 0.85 | | |
| | **UB** | 1.79* | 2.13* | 1.75* | 0.54 | 0.97 | 1.03 |
| | **RI** | 2.24* | 2.10* | 0.83 | 0.83 | | |
| | **LU** | 3.16* | 0.83 | 1.15 | 0.27 | | |
| **MF** | **TE** | 2.92* | 1.28 | 0.84 | 0.75 | | |
| | **FP** | 2.84* | 1.37* | 0.85 | 0.80 | | |
| | **RB** | 2.92* | 1.28 | 0.84 | 0.75 | | |
| | **UB** | 2.92* | 1.28 | 0.84 | 0.75 | | |
| | **RI** | 2.75* | 1.28 | 0.93 | 0.71 | | |
| **RF** | **TE** | 3.12* | 3.37* | 1.10 | 0.83 | | |
| | **FP** | 3.10* | 3.30* | 0.99 | 0.92 | | |
| | **RB** | 3.12* | 3.37* | 1.10 | 0.83 | | |
| | **UB** | 3.12* | 3.37* | 1.10 | 0.83 | | |
| | **RI** | 4.57* | 1.29* | 4.13* | 0.08 | 1.05 | 1.21 |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 13 Summary Results of Kolmogorov-Smirnov and Levene Tests for Evaluating the Effects of Glove, Thickness, Layer, and Task Demand on Tendon and Muscle Forces (Tweezers Tasks)

| **Tweezers** | | **Original Data** | | **Log10** | | **SQRT** | |
|---|---|---|---|---|---|---|---|
| **Digit** | | **KS** | **Levene** | **KS** | **Levene** | **KS** | **Levene** |
| **Th** | **FPL** | 2.82* | 5.63* | 0.97 | 0.79 | | |
| | **APB** | 2.55* | 4.36* | 1.74* | 0.78 | 1.82* | 1.77* |
| | **ADD** | 2.61* | 4.55* | 1.58* | 0.76 | 1.80* | 1.90* |
| **IF** | **TE** | 2.55* | 4.46* | 1.41* | 1.44* | 1.55* | 2.75* |
| | **FP** | 2.33* | 4.08* | 1.42* | 1.09 | 1.62* | 2.29* |
| | **RB** | 2.59* | 4.20* | 1.41* | 1.44* | 1.59* | 2.66* |
| | **UB** | 2.48* | 4.49* | 1.49* | 1.42* | 1.61* | 2.71* |
| | **RI** | 2.40* | 3.79* | 1.47* | 1.05 | 1.76* | 2.21* |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## Appendix 13 Summary Results of Kolmogorov-Smirnov and Levene Tests for Evaluating the Effects of Glove, Thickness, Layer, and Task Demand on Tendon and Muscle Forces (Wrench Tasks)

| **Wrench** | | **Original Data** | | **Log10** | |
|---|---|---|---|---|---|
| **Digit** | | **KS** | **Levene** | **KS** | **Levene** |
| **Thumb** | **FPL** | 3.27* | 2.72* | 0.87 | 0.49 |
| | **APB** | 2.92* | 3.39* | 1.18 | 0.61 |
| | **ADD** | 2.95* | 3.32* | 0.95 | 0.61 |
| **IF** | **TE** | 2.87* | 2.02* | 1.00 | 0.71 |
| | **FP** | 2.87* | 2.02* | 1.00 | 0.71 |
| | **RB** | 2.80* | 1.89* | 0.67 | 0.76 |
| | **UB** | 3.00* | 2.12* | 1.27 | 0.48 |
| | **RI** | 3.00* | 1.86* | 0.97 | 0.73 |
| | **LU** | 3.48* | 2.39* | 0.96 | 0.64 |
| **MF** | **TE** | 2.48* | 4.45* | 1.01 | 1.16 |
| | **FP** | 2.48* | 4.45* | 1.01 | 1.16 |
| | **RB** | 2.44* | 4.40* | 1.04 | 1.20 |
| | **UB** | 2.61* | 4.38* | 0.99 | 1.08 |
| | **RI** | 2.45* | 3.03* | 0.99 | 1.06 |
| | **LU** | 2.82* | 3.03* | 1.22 | 1.11 |

| | |
|---|---|
| * | Significance level of 0.05 |
| KS | Kolmogorov-Smirnov Z value |
| Levene | F-value |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

## References

**ADAC Corporation**, TestPoint Data Acquisition Software for Windows, Woburn, MA.

**AGS-G001-1998**, Guidelines for Gloveboxes, second edition, Santa Rosa, CA: American Glovebox Society.

**An, K.N., Chao E.Y., Cooney, W.P. and Linscheid, R.L.** 1979, Normative model of human hand for biomechanical analysis, Journal of Biomechanics, 12, pp. 775-88.

**An, K.N., Chao, E.Y., Cooney, W.P. and Linscheid, R.L.** 1985, Forces in the normal and abnormal hand, Journal of Orthopaedic Research, 3, pp. 202-11.

**Armstrong, T.J.** 1986, Ergonomics and cumulative trauma disorders, Hand Clinics, 2, pp. 553-65.

**ASTM F739**, Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases under Conditions of Continuous Contact, West Conshohocken, PA: American Society for Testing and Materials.

**ASTM F 1342**, Standard Test Method for Protective Clothing Material Resistance to Puncture, West Conshohocken, PA: American Society for Testing and Materials.

**ASTM F2010-00,** Standard Test Method for Evaluation of Glove Effects on Wearer Hand Dexterity Using a Modified Pegboard Test. ASTM International, 100 Barr Harbor Drive, PO Box 700, West Conshohocken, PA 19428-2959.

**ASTM G115-93,** Standard guide for measuring and reporting friction coefficients, Annual Books of ASTM standards, Vol 03.02.

**Batra, S., Bronkema, L.A., Wang, M.J., Bishu, R.R.** 1994, Glove attributes: can they predict performance?, International Journal of Industrial Ergonomics, 14, pp. 201-209.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Bellingar, T. and Slocum, A.C.** 1993, Effect of protective gloves on hand movement: an exploratory study, Applied Ergonomics, 24, pp. 244-250

**Bensel, C.K.** 1993, The effects of various thickness of chemical protective gloves on manual dexterity, Ergonomics, 36, pp. 687-696.

**Bishu, R.R. and Klute, G.** 1995, The effects of extra vehicular activity (EVA) gloves on human performance, International Journal of Industrial Ergonomics, 16, pp. 165-174.

**Bishu, R.R., Batra, S., Cochran, D.J. and Riley, M.W.** 1987, Glove effect on strength: an investigation of glove attributes, Proceedings of the Human Factors Society-31st Annual Meeting, pp. 901-905.

**Borg, G.** 1982, Psychophysical scaling with applications in physical work and the perception of exertion, Scandinavian Journal of Work, Environment and Health, 16 (suppl1), pp. 55-58.

**Bright, D.S. and Urbaniak, J.B. 1976,** Direct measurements of flexor tendon tension during active and passive digit motion and its application to flexor tendon surgery, Trans. of 22nd Ann. Mtg., Orthopaedic Research Society, pp. 240.

**Bronkema-Orr, L. and Bishu, R.R.** 1996, The effects of glove frictional characteristics and load on grasp force and grasp control, Proceedings of the Human Factors Society-40th Annual Meeting, September 2-6, Philadelphia, Pennsylvania, USA, pp. 702-706.

**Buhman, D.C., Cherry, J.A., Bronkema-Orr, L., Bishu, R.R.** 2000, Effects of glove, orientation, pressure, load, and handle on submaximal grasp force, International Journal of Industrial Ergonomics, 25, pp. 247-256.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Burke F.J.T., Wilson, N.H.F., and Wastell, D.G.** 1991, Gloves used in clinical practice: A survey of 2000 dentists in England and Wales, British Dental Journal, 171, pp. 128-132.

**Caldwell, L.S., Chaffin, D.B., Dukes-Dobos, F.N., Kroemer, K.H.E., Laubach, L.L., Snook, S.H.L. and Wasserman, D.E.** 1974, A proposed standard procedure for static muscle strength testing, American Industrial Hygiene Association Journal, 35, pp. 201-206.

**Chao E.Y., An, K.N., Cooney, W.P. III, and Linscheid, R.L. 1989,** Normative model of human hand, Biomechanics of the hand, World Scientific Publishing Company, pp. 5-30.

**Chao, E.Y., Opgrande, J.D. and Axmear F.E.** 1976, Three-dimensional force analysis of finger joints in selected isometric hand functions, Journal of Biomechanics, 9, pp. 387-396.

**Cochran, D.J., Albin, T.J., Bishu, R.R., Riley, M.W.** 1986, An analysis of grasp force degradation with commercially available gloves, Proceedings of the Human Factors Society-30th Annual Meeting, September 29-October 3, 1986, Dayton, Ohio, USA, pp. 852-855.

**Cooney, W.P. III and Chao, E.Y.** 1977, Biomechanical analysis of static forces in the thumb during hand function, Journal of Bone and Joint Surgery American, 59, pp. 27-36.

**Eastman Kodak Company** 1983, Ergonomic Design for People at Work Volume I: Workplace, Equipment, and Environmental Design and Information Transfer, Eastman Kodak Company, Van Nostrand Reinhold, New York.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Edin, B.B., Westling, G., Johansson, R.S.** 1992, Independent control of human finger-tip forces at individual digits during precision lifting, Journal of Physiology, 450, pp. 547-564.

**Fellows, G.L. and Freivalds, A.** 1989, The use of force sensing resistors in ergonomic tool design, Proceedings of the Human Factors Society 33rd Annual Meeting, October 16-20, 1989, Denver, Colorado, USA, pp. 713-717.

**Fransson-Hall, C. and Kilbom, A.** 1993, Sensitivity of the hand to surface pressure, Applied Ergonomics, 24, pp. 181-189.

**Fraser, T.M.** 1980, Ergonomic principals in the design of hand tools, Occupational Safety and Health Series No. 44 (Geneva: International Labour Office).

**Gross C M 1988,** Diagnostic criteria for cumulative trauma disorders of the upper extremity, Biomechanics Corporation of America, Melville, New York.

**Groth H. and Lyman, J.** 1958, Effects of surface friction on skilled performance with bare and gloved hand, Journal of Applied Psychology, 42, pp. 273-277.

**Hallbeck M.S. and McMullin, D.L.** 1993, Maximal power grasp and three-jaw chunk pinch force as a function of wrist position, age, and glove type, International Journal of industrial Ergonomics, 11, pp. 195-206.

**Hallbeck, M.S.** 1995, Flexion and extension forces generated by wrist-dedicated muscles over the range of motion, Applied Ergonomics, 25, pp. 379-385.

**Hardy, J.D., Wolff, H.G., Goodell, H. and Boring, E.G. 1967,** Pain sensations and reactions, Hafner Publishing Company, New York.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Imrhan, S.N., Nguyen, M.T. and Nguyen, N.N.** 1993, Hand anthropometry of Americnas of Vietnamese origin, International Journal of Industrial Ergonomics, 12, pp. 281-287.

**Jensen, T.R., Radwin, R.G., Webster, J.G.** 1991, A conductive polymer sensor for measuring external finger forces, Journal of Biomechanics, 24, pp. 851-858.

**Keithley Inc.**, http://www.keithley.com/main.jsp, Corporate Headquarters
Keithley Instruments, Inc., 28775 Aurora Road, Cleveland, Ohio 44139

**Kinoshita, H., Kawai, S., and Ikuta, K.** 1995, Contributions and co-ordination of individual fingers in multiple finger prehension, Ergonomics, 38, pp. 1212-1230.

**Kinoshita, H.** 1999, Effect of gloves on prehensile forces during lifting and holding tasks, Ergonomics, 42, pp. 1372-1385.

**Kom Kare com.**, Middletown, Ohio 45042, http://www.komkare.com/kkc_home.html.

**Kovacs K, Splittstoesser R, Maronitis A, Marras WS.** 2002, Grip force and muscle activity differences due to glove type, American Industrial Hygiene Association Journal, 63, pp. 269-74.

**Kovavisarach, E. and Vanitchanon, P.** 1999, Perforation in single- and double-gloving methods for cesarean section, International Journal of Gynecology and Obstetrics, 67, pp. 157-161.

**Knudson, D.V. and White, S.C.** 1989, Forces on the hand in the tennis forehand drive: Application of Force Sensing Resistors, International Journal of Sport Biomechanics, 5, pp. 324-331.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Lafayette Instrument Company**, http://www.lafayetteinstrument.com/, Lafayette, Indiana 47903.

**Lawrence Berkeley National Laboratory** 2006, http://eetd.lbl.gov/EHS/Lessons/Glovebox.html, 1 Cyclotron Road, Berkeley CA 94720.

**Liu, V.W.C., Sung, P.C., Arias, L., Hollander, J., MacDonald, J.** 2000, Use of glovebox gloves and its ergonomic impacts, American Industrial Hygiene Conference and Exposition Abstract, May 20-25, Orlando, Florida, USA, pp. 10.

**Marin-Bertolin, S., Gonzales-Martinez, R., Gimenez, C.N., Marquina, V.P. and Amorrortu-Velayos, J.** 1997, Does double gloving protect surgical staff from skin contamination during plastic surgery?, Plastic and Reconstructive Surgery, 99 (4), pp. 956-960.

**Mathiowetz, V., Kashman, N., Volland, G., Weber, K., Dowe, M.** 1985, Grip and pinch strength: normative data for adults, Arch Phys Med Rehabil, 66, pp. 69-74.

**Microsoft Visual Basic** 1987-1998, Version 6.0, Microsoft Corporation.

**Moberg E. 1990,** Two-point discrimination test, Scandinavian Journal of Rehabilitation Medicine, 22, pp. 127-134.

**Muralidhar, A. and Bishu, R.R.** 1994, Glove evaluation: a lesson from impaired hand testing, Advances in Industrial Ergonomics and Safety IV, Edited by F. Aghazadeh, Taylor and Francis, pp. 619-625.

**Muralidhar, A. and Bishu, R.R.** 2000, Safety performance of gloves using the pressure tolerance of the hand, Ergonomics, 43, pp. 561-572.

**Muralidhar, A., Bishu, R.R., and Hallbeck, M.S.** 1999, The development and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

evaluation of an ergonomic glove, Applied Ergonomics, 30, pp. 555-563.

**Napier, J.R.** 1956, The prehensile movements of the human hand, The journal of bone and joint surgery, 38B, pp. 902-913.

**Naver, L.P.S. and Gottrup, F.** 2000, Incidence of glove perforations in gastrointestinal surgery and the protective effect on double gloves: A prospective, randomized controlled study, European journal of surgery, 166, pp. 293-295.

**Neiburger, E.J.** 1992, Latex gloves and manual dexterity, The New York State Dental Journal, 1, pp. 24-28.

**Nelson, J.B. and Mital, A.** 1995, An ergonomic evaluation of dexterity and tactility with increase in examination/surgical glove thickness, Ergonomics, 38, pp. 723-733.

**NFPA** 1999, Standard on Protective Clothing for Emergency Medical Operations, National Fire Protection Association, Quincy, MA.

**NIOSH 1997**, Musculoskeletal disorders and workplace factors - A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back, Bernard, B. P. edited, NIOSH publication 97-104, National Institute of Occupational Safety and Health, Cincinnati, OH.

**Northern tool company**, Burnsville, Minnesota 55306, http://www.northerntool.com/.

**Novak, C.B., Megan, J., Patterson, M. and Mackinnon, S.E.** 1998, Evaluation of hand sensibility with single and double latex gloves, Plastics and Reconstructive Surgery, 103, pp. 128-131.

**Okunribido, O.O.** 2000, A survey of hand anthropometry of female rural farm workers in Ibadan, Western Nigeria, Ergonomics, 43, pp. 282-292.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Olsen, C.H.** 2003, Review of the Use of Statistics in Infection and Immunity, Journal of Infection Immunity, 71, pp. 6689-6692.

**OMEGA** 2006, http://www.omega.com, OMEGA Engineering Inc., Stamford, Connecticut.

**Pieper, S.P., Schimmele, S.R., Johnson, J.A., Harper, J.L.** 1995, A prospective study of the efficacy of various gloving techniques in the application of Erich arch bars, Journal of Oral and Maxillofacial Surgery, 53, pp. 1174-6; discussion 1177.

**Plummer, R., Stobbe, T., Ronk, R., Myers, W., Kim, H. and Jaraiedi, M.** 1985, Manual dexterity evaluation of gloves used in handling hazardous materials, Proceeding of the Human Factors Society-29th annual meeting, September 29-October 3, 1985, Baltimore, Maryland, USA, pp. 819-823.

**Putz-Anderson, V.** (ed.) 1988, Cumulative trauma disorders: A manual for musculoskeletal diseases of the upper limbs. Taylor & Francis.

**Riley, M.W. and Cochran, D.J.** 1988, Ergonomic aspects of gloves: design and use, International Reviews of Ergonomics, 2, 233-250. Edited by David J. Oborne, Taylor & Francis.

**Riley, M.W., Cochran, D.J. and Schanbacher, C.A.** 1985, Force capability difference due to gloves, Ergonomics, 28, pp. 441-447.

**Roberts, A.D. and Brackley, C.A.** 1996, Comfort and frictional properties of dental gloves, Journal of Dentistry, 24, pp. 339-343.

**Rock, K.M., Mikat, R.P., Foster, C.** 2001, The effects of gloves on grip strength and three-point pinch, Journal of hand therapy, 14, pp. 286-90.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Rosier, R. and Blair, W.** 1984, Preliminary clinical evaluation of the digital electroneurometer, Biomedical Sciences Instrumentation, 20, pp. 55-59.

**Shand's health care**, http://www.shands.org/health/information/article/003206.htm.

**Sudhakar, L.R., Schoenmarklin, R.W., Lavender, S.A. and Marras, W.S.** 1988, The effects of gloves on grip strength and muscle activity, Proceedings of the Human Factors Society-32nd annual meeting, October 24-28, 1988, Anaheim, California, USA, pp. 647-650.

**Sung, P.C. and Liu, V.W.C.** 2002, Effects of Glovebox Gloves and Task Positions on Contact Force, American Industrial Hygiene Conference and Exposition Abstract, June 1-6, 2002, San Diego, California, USA, 11.

**Tekscan, Inc.** 2006, http://www.tekscan.com, 307 West First Street, South Boston, MA 02127-1309.

**The Free Dictionary** 2005, http://www.thefreedictionary.com/discomfort, Farlex, Inc.

**Thompson, P.B. and Lambert, J.V.** 1995, Touch sensibility through latex examination gloves, The Journal of General Psychology, 122, pp. 47-58.

**Tichauer, E.R. and Gage, H.** 1977, Ergonomic principals basic to hand tool design, American Industrial Hygiene Association Journal, 38, pp. 622-634.

**Tsaousidis, N. and Freivalds, A.** 1998, Effects of gloves on maximal force and the rate of force development in pinch, wrist flexion and grip, International Journal of Industrial Ergonomics, 21, pp. 353-360.

**Vasu, M. and Mital, A.** 2000, Evaluation of the validity of anthropometric design assumptions, International Journal of Industrial Ergonomics, 26, pp. 19-37.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

**Wang, M.-J. J. 1991**, The effects of six different kinds of gloves on grip strength, in M. Kumashiro and E.D. Megaw (eds), Towards Human Work: Solutions to Problems in Occupational Health and Safety (Taylor and Francis, London), pp. 164-169.

**Watts, D., Tassler, P.L. and Dellon, A.L.** 1994, The effect of double gloving on cutaneous sensibility, skin compliance, and suture identification, Contemporary Surgery, 44, pp. 289-292.

**Westling, G. and Johansson, R.S.** 1984, Factors influencing the force control during precision grip, Experimental Brain Research, 53, pp. 277-284.

**Wilson, S.J., Sellu, D., Uy, A. and Jaffer, M.A.** 1996, Subjective effects of double gloves on surgical performance, Annals of the Royal College of Surgeons of England, 78, pp. 20-22.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.