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Biomechanical Assessment of Muscle Forces of Thumb and Fingers for Simulated Glovebox Tasks with Three Commonly used Hand Tools

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Abstract: This study predicted the muscle forces of thumb and fingers for simulated glovebox tasks with three hand tools using a three-dimensional (3D) biomechanical model. Then, this study evaluated the effects of glove materials, layer of gloves donned, and glove thickness on the muscle forces. The results found muscle forces on three thumb muscles for all simulated tasks. The computed solutions also found muscle forces on five muscles in index finger for all tasks, in middle finger for roller and wrench tasks, and in ring finger for roller tasks. In addition, forces in lumbrical (LU) muscle were found in index finger for roller and wrench tasks and in middle finger for wrench tasks. To minimize the mechanical stress on muscles of the hand, hypalon material could be selected since it could offer protection for thumb and ring fingers with the lowest muscle forces recorded. Triple gloving could also be selected to lower the muscle forces of the thumb and the index and ring fingers. In addition, use of thinner glovebox gloves can retain better grip and pinch strength and tactility of the working hand.

Keywords: muscle force; hand tool; biomechanical model; glovebox glove; musculoskeletal disorders.

1. Introduction

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 [1]. In glovebox operations, workers are required to wear up to three layers of gloves to offer protection to the hand against hazardous chemicals, biological, mechanical and radiological hazards. 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 [1]. High compression on the hand will cause tissue irritation, followed by inflammation and formation of callus tissue [2]. Barbe and Barr's [3] also hypothesized that tendon tissue inflammation resulted from task exposure is one of the three pathways that induce musculoskeletal disorders (MSDs) for hand-intensive tasks.

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Work-related musculoskeletal disorders (MSDs), also called overuse injuries, have accounted for a significant proportion of work injuries and workers' compensation claims in Western industrialized nations since the late 1980s [3]. For the hand and wrist MSDs, epidemiological research associates the onset and severity of disorders with the performance of repetitive and forceful hand-intensive tasks [4]. 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 [5]. Therefore, assessment of muscle forces can help explain how external forces are transmitted to the internal muscles and identify which muscles are highly exposed to these external forces for hand-intensive tasks [6]. In addition, the muscle forces obtained can better the understanding of hand function and be used to evaluate mechanical causes for hand pathologies associated with the using of hand tools for glovebox tasks.

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 [7]. 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 internal force analysis, biomechanical models have been used to calculate two-dimensional (2D) and three-dimensional (3D) muscle forces production with measured external forces of single and/or multiple fingers. Since the human hand is a three-dimensional structure and the glovebox tasks performed in this study require 3D force exertions, 3D models used to estimate muscles forces were considered in this study.

For 3D force analysis, most biomechanical models were developed to predict tendon/muscle tensions for thumb [8-11] or individual digit [12-15]. For multiple fingers modeling, Chao et al. [16] 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). An et al. [17] estimated muscle forces for four fingers in four basic isometric hand functions (tip pinch, lateral pinch, ulnar pinch and grasp). An et al. [7] refined the model developed by Chao et al. [16] by examining additional objective functions for solutions using the optimization methods. Chao et al. [18] refined An et al.'s model [17] by adding the coefficient of force and moment potential for the thumb to estimate the muscles forces for the thumb in addition to the four fingers.

Upon reviewing the articles, Chao et al.'s 3D biomechanical model [18] was adopted in the present study to estimate muscle forces for fingers and thumb. This model was chosen based on 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) which are related to the tasks performed in this study. In addition, Vigouroux et al. [19] shows that Chao et al.'s model [18] predicted relevant muscle coordination for five of the nine muscles modeled when compared and correlated computed tendon tensions to electromyographic (EMG) measurements provided in the literature. Only Opponent and abductor longus muscle coordinations were badly estimated.

The aim of this study is to predict muscle forces using contact forces obtained in previous study [20] for simulated glovebox tasks with three commonly used hand tools. Then, this study will evaluate the effects of glovebox gloves, layer of gloves donned, and thickness of glove on the muscle forces computed using the selected 3D biomechanical model.

2. Methods

2.1. Subjects

Eleven volunteered female free of MSDs in the upper extremities comprised the subject pool [20]. The subject's free of MSDs status in the upper extremities was identified through interviewing during the recruiting process. 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 detailed information regarding linkage length parameters required for Chao et al.'s model can be found in Sung's study [20].

2.2. External Contact Forces Measurements

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 [20]. Butyl, hypalon and neoprene gloves in two different thicknesses (0.015" and 0.03") that are commercially available for glovebox use were selected for evaluation. Two hand sizes, 8.5"and 9.75" were provided and the subject wore both of the gloves to pick the best fit glove. 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.

Three hand tools (Figure 1), namely a roller, a crescent wrench (3/4"), and a pair of tweezers were used for task simulations. These tools are used for glovebox work and for common maintenance/production activities in the nuclear industry. A maximum of four force sensing resistors (FSRs, Tekscan Inc.) 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 H9 palm region [21].

Simulated tasks (Figure 2, wrench task simulation) 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 displayed on the screen of a computer monitor during the test, then, hold that force or torque for approximately one second. The same procedure was repeated three times. For roller and tweezers, the target task demands represented 25%, 50%, and 75% of the maximum voluntary force, 40 Newton (N) and 20 Newton (N), exertions of the roller and tweezers measured from three female subjects in previous study [22]. For wrench tasks, the highest target task demand (9.04 Nm, Newton-meter) 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 (9.04 Nm) 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.

Figure 1. Three hand tools: roller (left), tweezers (middle), and wrench (right)

Figure 2. Wrench task simulation inside a typical glovebox (the subject did not wear glove to show the FSRs connection).

2.3. Biomechanical Model

The muscles involved in the hand functions are listed in Table 1 [18]. Six Cartesian coordinate systems were established to define the locations and orientation of muscles. There are two coordinate systems for both the middle and proximal phalanges and only one system for both the distal phalanx and metacarpal. Two parameters, “force potential’ and “moment potential”, were used to describe the orientation and location of each muscle. The force potential is expressed in terms of the directional cosine of a muscle with respect to the distal system. It provides the contribution of a particular muscle in generating joint constraint forces. The moment potential specifies the moment arm of the muscle 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 muscle in rotating the joint at three mutually perpendicular directions. Equations 1 and 2 are equilibrium equations for force and moment at the distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint, and metacarpo-phalangeal (MP) joint for the fingers and the interphalangeal (IP) joint, metacarpo-phalangeal joint (MP), and the carpometacarpal (CMC) joint for the thumb:

Force equations

$$\begin{aligned} \Sigma\ \alpha_i F_i + C_x + R_x &= 0 \\ \Sigma\ \beta_i F_i + C_y + R_y &= 0 \\ \Sigma\ \gamma_i F_i + C_z + R_z &= 0 \end{aligned} \tag{1}$$

Moment equations

$$\begin{aligned} \Sigma\ a_i F_i + M_x + T_x &= 0 \\ \Sigma\ biFi + My + Ty &= 0 \\ \Sigma\ c_i F_i + M_z + T_z &= 0 \end{aligned} \tag{2}$$

where

α_i, β_i, γ_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 muscle forces,
R_x, R_y, R_z = externally applied forces, and
T_x, T_y, T_z = externally applied moments.

The required input parameters for using this model are externally applied force and the flexion-extension (φ), radioulnar deviation (θ), and pronation-supination (ψ) 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 muscle forces and joint constraint forces and moments.

The externally applied forces were the contact forces measured in previous study [20]. 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 tools in static mode since no electrical 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 were in neutral positions [7] 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 (equation 3) was performed so that the muscle and the externally applied forces could be defined in the same coordinate system for the force analysis.

in which,

$$\begin{bmatrix} X_D \\ Y_D \\ Z_D \end{bmatrix} = \begin{bmatrix} c\theta c\phi & c\theta s\phi & -s\theta \\ -c\psi s\phi + s\psi s\theta c\phi & c\psi c\phi + s\psi s\theta s\phi & s\psi c\theta \\ s\psi s\phi + c\psi s\theta s\phi & -s\psi c\phi + c\psi s\theta s\phi & c\psi c\theta \end{bmatrix} \times \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \tag{3}$$

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.

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 were made to reduce the unknowns to make the problems statistically determinate [8]. The first assumption is that the extensor pollicis longus and extensor pollicis brevis muscles 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 muscle 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 muscle 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 [16] were used to find and discard the inadmissible solutions.

1. any of the muscles 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.

2.4. Computer Program

A computer program 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 transformation of externally applied contact forces using formula 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.

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

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 equation 4 to calculate the solution array {x}using the back substitution method.

$$xi = \frac{1}{a'ii}\left(b'i - \sum_{j=i+1}^{k} a'ijxj\right) \tag{4}$$

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 muscle 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.

Table 1. Tendons and muscles involved in hand function

Hand element	Joint	Tendons and muscles
Finger[1]	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[2]	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)

[1] Finger joint: DIP (distal interphalangeal joint); PIP (proximal interphalangeal joint); MP (metacarpo-phalangeal joint).

[2] Thumb joint: IP (interphalangeal joint); MP (metacarpo-phalangeal joint); CMC (carpometacarpal joint).

2.5. Experimental Design and Statistical Analysis

The dependent variables are the predicted muscle forces. This study evaluated the effects of glove material, thickness, layer, and target task demand on the muscle forces. The target 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 [23].

Analyses of variance (ANOVAs) with repeated measures were used to determine whether there were significant differences among independent variables. Then, Bonferroni post hoc analyses were performed to determine which pairs of means were significantly different. All data were analyzed for statistical significance at $p \le 0.05$ using the SPSS 12.0 (SPSS Inc, Chicago, Illinois) statistical software.

3. Results

3.1. Estimated Muscle Forces

Applying Chao et al.’s [18] 3D biomechanical model, computed solutions found muscle force at the flexor pollicis longus (FPL), abductor pollicis brevis (APB), and adductor pollicis (ADD) of the thumb and at the terminal extensor (TE), flexor profundus (FP), radial band (RB), ulnar band (UB), radial interosseous (RI) of the fingers for all three tasks. The computed solution also showed that forces existed at the lumbrical muscle (LU) of the index finger during roller tasks simulation and of the index and middle fingers during wrenching tasks.

Table 2 shows the range of computed muscle forces for all the functional muscles (muscle force > 0) obtained in this study (detailed data is not presented here). For the tweezers tasks, estimated muscle forces ranged from 5.5 N (FPL) to 182.1 N (APB) and 9.4 N (UB) to 125.9 N (FP) for the thumb and index finger, respectively. For the roller tasks, estimated muscle forces ranged from 6.8 N (FPL) to 139.7 N (APB), 5.9 N (UB) to 45.4 N (TE), 9.4 N (UB) to 78.2 N (FP), and 2.6 N (RI) to 81.6 N (FP) for the thumb, index finger, middle finger, and ring finger, respectively. For the wrench tasks, estimated muscle forces ranged from 4.7 N (FPL) to 106.7 N (APB), 3.3 N (UB) to 30.6 N (TE), and 2.3 N (LU) to 50.3 N (TE) for the thumb, index finger, and middle finger, respectively. From the computed results, the ratio of forces on FPL, APB, and ADD to target task demand ranged from 1.08 to 1.80, 7.59 to 12.14, and 5.13 to 8.18, respectively. Table 3 shows the ranges of ratio for all the functional muscles (muscle force > 0) obtained in this study (detailed data is not presented here). The ratios shown in table 3 for wrench tasks were computed as muscle force to the target tasks demand in torque (not force) and provided here for reference only.

3.2. Effects on Muscle Forces

Tables 4 and 5 summarize the repeated-measures ANOVA results for the effects of glove material and layer on the muscle 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 ($p<0.01$). The layer factor is statistically significant for the forces in FPL, APB, and ADD of the thumb ($p<0.01$) and in TE, FP, RB, RI, and LU of index finger ($p<0.05$) for the roller tasks. The layer factor is also statistically significant for the forces in FPL of the thumb for tweezers tasks ($p<0.01$) and in FPL, APB, and ADD of the thumb for wrench tasks ($p<0.01$). 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 muscles treated with repeated-measures ANOVAs. No statistically significant effects for thickness on muscle forces were found.

Table 2. Range of estimated forces (N) in thumb and finger muscles for three simulating glovebox tasks

Digit[1]	**Tools**	**Muscles**					
Th		**FPL**	**APB**	**ADD**			
	Roller	6.8-20.8	48.4-139.7	34.1-97.8			
	Tweezers	5.5-26.9	38.6-182.1	26.0-122.7			
	Wrench	4.7-19.9	26.2-106.7	18.4-74.8			
IF		**TE**	**FP**	**RB**	**UB**	**RI**	**LU**
	Roller	17.9-45.4	16.9-42.8	11.9-29.9	5.9-15.5	14.2-36.3	9.1-24.7
	Tweezers	24.4-97.4	31.8-125.9	13.7-56.3	10.5-41.1	14.9-58.4	---
	Wrench	9.6-30.6	9.0-28.8	6.3-20.3	3.3-10.3	7.4-23.9	4.5-15.4
MF		**TE**	**FP**	**RB**	**UB**	**RI**	**LU**
	Roller	23.9-70.3	26.5-78.2	14.6-42.8	9.4-27.5	10.2-28.5	---
	Wrench	9.2-50.3	8.2-44.7	5.8-31.7	3.4-18.6	6.9-39.0	2.3-13.0
RF		**TE**	**FP**	**RB**	**UB**	**RI**	
	Roller	18.9-77.6	19.9-81.6	9.5-39.1	9.4-38.5	2.6-9.2	

[1] Th (thumb); IF (index finger); MF (middle finger); RF (ring finger).

Table 3. The range of ratios computed as muscle forces to target task demand for three simulating glovebox tasks

Digit[1]	**Tools**	**Muscles**					
Th		**FPL**	**APB**	**ADD**			
	Roller	0.41-0.93	2.82-6.54	1.87-4.60			
	Tweezers	1.08-1.80	7.59-12.14	5.13-8.18			
	Wrench	1.16-8.24	6.49-44.30	4.53-31.63			
IF		**TE**	**FP**	**RB**	**UB**	**RI**	**LU**
	Roller	1.19-2.66	1.12-2.51	0.79-1.77	0.40-0.90	0.96-2.14	0.62-1.39
	Tweezers	4.71-6.54	6.04-8.53	2.66-3.75	1.97-2.86	2.83-4.09	---
	Wrench	2.39-12.40	2.26-11.69	1.59-8.16	0.80-4.24	1.86-10.20	1.14-6.59
MF		**TE**	**FP**	**RB**	**UB**	**RI**	**LU**
	Roller	1.25-4.46	1.39-4.96	0.76-2.72	0.49-1.75	0.57-1.85	---
	Wrench	3.90-12.68	3.47-11.28	2.43-8.22	1.47-4.46	2.99-9.52	0.84-4.15
RF		**TE**	**FP**	**RB**	**UB**	**RI**	
	Roller	1.28-4.36	1.33-4.60	0.64-2.19	0.63-2.16	0.16-0.42	

[1] Th (thumb); IF (index finger); MF (middle finger); RF (ring finger).

Table 4. Summary of repeated-measures ANOVA results (F value) for effects of glove material on muscle forces for three tools for eleven female subjects

Digit	**Tool**	**Muscle**					
Thumb		**FPL**	**APB**	**ADD**			
	Roller	1.11	1.09	1.09			
	Tweezers	2.90	2.16	2.12			
	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	---

*: $p < 0.05$; **: $p < 0.01$

Table 5. Summary of repeated-measures ANOVA results (F value) for effects of layer on muscle forces for three tools for eleven female subjects

Digit	**Tool**	**Muscle**					
Thumb		**FPL**	**APB**	**ADD**			
	Roller	9.53^{**}	7.47^{**}	9.52^{**}			
	Tweezers	11.66^{**}	2.98	3.04			
	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	---

*: $p < 0.05$; **: $p < 0.01$

3.2.1. Glove Material Effects

Figure 3 shows the means and standard errors of the muscle forces in FPL, APB and ADD of the thumb for wrenching tasks. Bonferroni post hoc analyses results indicated that Butyl material increased the muscle forces significantly (p<0.01) compared to hypalon material in all three muscles. Figure 4 shows the means and standard errors of the muscle force in TE, FP, RB, and UB of the ring finger for roller tasks. The Bonferroni post hoc comparisons indicated that neoprene material increased the forces significantly (p<0.05) compared to hypalon material.

3.2.2. Layer Effects

Table 6 shows the Bonferroni post hoc tests of layers for muscles showing significant differences treated with repeated-measures ANOVA. For roller tasks, 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 the ring finger ($p<0.05$). For tweezers tasks, single layer increased the forces significantly compared to double and triple layers in FPL of the thumb ($p<0.05$). 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 ($p<0.05$).

3.2.3. Task demand Effects

For the task demand factor, all three levels differed significantly from one another in all muscles ($p<0.001$) treated with repeated-measures ANOVAs except in the FPL, APB, and of the thumb for wrench tasks where significant mean differences were only found to be between the target task demands of 9.04 N-m and 1.13 N-m ($p<0.05$).

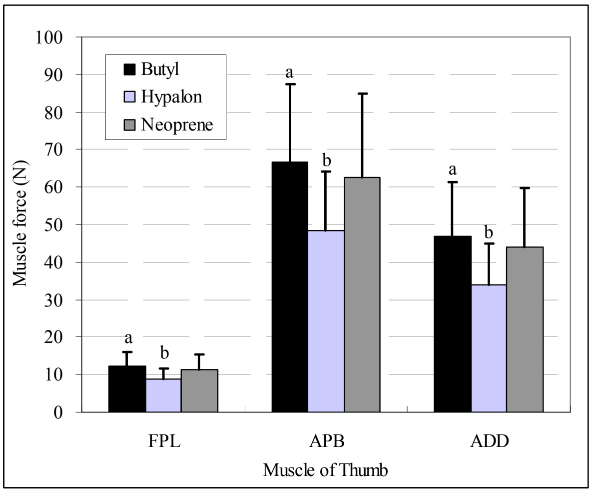

Figure 3. Means and standard errors of the muscle force of the thumb when performing wrench tasks with different glovebox gloves (N=11; a and b: significantly level at $p<0.01$)

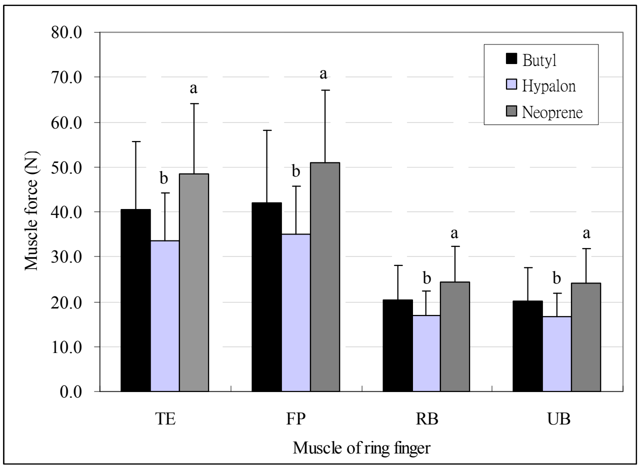

Figure 4. Means and standard errors of the muscle force of the thumb when performing wrench tasks with different glovebox gloves (N=11; a and b: significantly level at $p<0.05$)

Table 5. Summary of repeated-measures ANOVA results (F value) for effects of layer on muscle forces for three tools for eleven female subjects

Digit	**Tool**	**Muscle**					
Thumb		**FPL**	**APB**	**ADD**			
	Roller	9.53^{**}	7.47^{**}	9.52^{**}			
	Tweezers	11.66^{**}	2.98	3.04			
	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	---

*: $p < 0.05$; **: $p < 0.01$

Table 6. Bonferroni post hoc tests of layer for muscles showing significant differences treated with repeated-measures ANOVA

Tool	**Digit**	**Muscle**	**Layer***		
Roller	**Thumb**	FPL, APB, ADD	Double	Single	Triple
	IF	TE, FP, RB, UB, RI, LU	Double	Single	Triple
	RF	RI	Double	Single	Triple
Tweezers	**Thumb**	FPL	Single	Double	Triple
Wrench	**Thumb**	FPL, APB, ADD	Single	Double	Triple

*: The muscle force in the left column of layer is greater (p<0.05).

4. Discussion

This study used Chao et al.'s 3D biomechanical model [18] for predicting forces in muscles of thumb and fingers associated with simulated glovebox tasks with three hand tools. From the computed solutions, three out of the eight thumb muscles (FPL, APB, and ADD) are the functional muscles (muscle force > 0) of the thumb for all three simulated tasks. Five out of ten muscles (TE, FP, RB, UB, and RI) are the functional muscles in index finger for all three tasks, in middle finger for roller and wrench tasks, and in ring finger for roller tasks. In addition, LU is found as functional muscle in index finger for roller and wrench tasks and in middle finger for wrench tasks.

The only available direct measurements of in vivo tendon(muscle) forces were reported by Bright and Urbaniak [24] where the FP force of index finger 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 the forces (table 2) obtained for roller and wrench tasks in grasp hand functions, the values reported by Bright and Urbaniak [24] are relatively higher than the theoretical estimated results shown in the present study (9.0-42.8 N). For tweezers tasks, the muscle force predicted in FP of this experiment was computed to be in the ranges of 3.2-12.8 Kg (31.8-125.9 N). The force data are a little bit higher than but not far from the ranges of 2.5-12.5 kg (24.5-122.6 N) in tip pinch hand function reported by Bright and Urbaniak [24].

To understand how functionally relevant tasks affect the biological tissues, it is necessary to determine the internal loads borne by the muscles, joints, and soft tissues [25] since force is a fundamental mechanism associated with injury. If the forces in a tissue exceed the tolerance of the tissue, then the tissue will fail and be injured such as an excessive strain, tear, or fracture [26]. In this study, the ranges of the forces (descriptive data not shown here) that exist in the finger and thumb during three simulated activities were provided (table 2). In addition, the ratios of muscle force to target tasks demand for all functional muscles were also computed (table 3). The forces in the muscles of the thumb (APB) and index finger (FP) can be as large as 12.0 and 8.5 times the forces required to perform the tweezers tasks, respectively. For roller tasks, the forces in the muscles of the thumb (APB) and middle and ringers (FP) can be as large as 6.5 and 4.6-5.0 times the forces required, respectively. The muscle forces data provided in this study can be used to better the tendon repair techniques, rehabilitation procedures, and joint replacement designs [6]. The non-functional muscles for these three tasks could also be selected as substitution for the abnormal functional muscles once a muscle/tendon transfer is required to restore the function and strength of the hand. In addition, the force and ratio data can be used as selection criteria for the available and under consideration muscles.

The effects of glove, layer, and thickness on muscle forces were similar to that of the effects on contact forces [20] 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 muscles.

For the effects of glove material on muscle forces, the present investigation found that hypalon material reduced the forces significantly compared to neoprene material in TE, FP, RB, and UB of the ring finger for roller task (Figure 4). Hypalon material also reduced the forces significantly compared to butyl material in FPL, APB and ADD of the thumb for wrench tasks (Figure 3). For the effects of layer on muscle forces, this study found that 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 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.

To minimize the mechanical stress (optimize protection) on 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 muscle forces recorded. In addition, triple gloving could be used to lower the muscle forces of the thumb, the index and ring fingers. Although no statistically significant effects for thickness on muscle forces were found, this study recommends the use of thinner (0.015”) glovebox glove since it can retain better grip and pinch strength and tactility [20] of the working hand.

So far, it is still difficult and challenging to measure the internal force on biological tissues from the external activities. Direct measures (e.g. by means of invasive transducers) bypass many of the limitations associated with modeling efforts, however, they are quite invasive and difficult to perform on humans from an ethical viewpoint [26]. Evaluations based on comparison of normalized electromyographic (nEMG) recordings can also be problematic if the test conditions involve different postures or joint and velocities [25] and may not be able to reflect the actual internal loading. Biomechanical models are increasingly used to predict the internal loads, however, ideally models should be scaled based upon individually collected parameter sets [27] and be validated in advance.

Despite the paramount functions of the hand in daily life, hand biomechanical models have been little developed, evaluated, and validated. The performances of the biomechanical model adopted in this study had been evaluated by Vigouroux et al. [19] through nEMG measurements provided in the literature. However, they made evaluation on the internal loadings on the muscles of thumb only. They also points out the necessity of new anthropometric measurements of thumb tendon location strongly related to a relevant and in vivo reproducible kinematic description. Therefore, further reliable verification of the mathematical solutions presented in this study awaits the development of better biomechanical models and/or experimental validation.

5. Conclusion

From the computed solutions of this study, we concluded that the FPL, APB, and ADD are the functional muscles of the thumb for the simulated tweezers, roller, and wrench tasks. TE, FP, RB, UB, and RI are also the functional muscles in index finger for all three tasks, in middle finger for roller and wrench tasks, and in ring finger for roller tasks. In addition, LU is the functional muscle in index finger for roller and wrench tasks and in middle finger for wrench tasks. To minimize the mechanical stress on muscles of the hand, hypalon material could be selected since it could offer protection for thumb and ring finger with the lowest muscle forces recorded. Triple gloving could also be selected to lower the muscle forces of the thumb and the index and ring fingers. In addition, this study recommends the use of thinner (0.015”) glovebox glove since it can retain better grip and pinch strength and tactility of the working hand.

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